Appendix A

Performance Modeling Report

Modeling for Conceptual Design of an Evapotranspiration Cover for the Present Landfill at the Rocky Flats Environmental Technology Site

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April 15, 2002

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Appendix A.
Modeling for Conceptual Design of an Evapotranspiration Cover for the Present Landfill at the Rocky Flats Environmental Technology Site

A.1 Introduction

Daniel B. Stephens & Associates, Inc. (DBS&A) was contracted by Kaiser-Hill, LLC to perform modeling, conceptual design, and related activities for an evapotranspiration (ET) cover for the Present Landfill at the Rocky Flats Environmental Technology Site (RFETS). This report presents the results of the modeling activities conducted to support the design of ET soil cover at this site. The primary objective of the modeling is to evaluate the potential for water movement through the ET cover into the underlying waste at the Present Landfill and demonstrate the ET cover performance equivalence to standard cover designs.

Water balance modeling uses a soil's water-holding capacity characteristics to determine the cover thickness adequate to reduce infiltration. The ET cover for the Present Landfill must provide infiltration reduction equivalent to a standard cover design. The modeling discussed in this report compared the ET cover's effectiveness versus a conventional design that includes synthetic and clay barrier layers..

The unsaturated models HELP, HYDRUS-2D, EPIC, SoilCover, and UNSAT-H were reviewed for use in designing the landfill cover for the Present Landfill. Each of the models has strengths and weaknesses for landfill applications in general and for RFETS modeling in particular. One limitation common to several of the models is that slopes, topography, and runoff are either considered in two dimensions only (HYDRUS-2D) or are greatly simplified. Appendix D of the *Conceptual Design for the Present Landfill Closure Cover Rocky Flats Environmental Technology Site* (Conceptual Design Report) contains a detailed model selection report that compares the unsaturated models and their advantages and disadvantages.

The UNSAT-H model was used for the RFETS modeling for the following reasons:

- It is a physically based model that accurately describes water movement and redistribution in unsaturated soil systems such as landfill covers.

- It has been successfully used at the nearby Rocky Mountain Arsenal (RMA) and Fort Carson.

- Intricacies of the model are well understood by consultants and regulators involved in the project.

- Results from previous modeling exercises using UNSAT-H have been accepted by the Colorado Department of Public Health and Environment (CDPHE).

- UNSAT-H has been widely used on many alternative cover projects in recent years and has been the primary model used to design landfill covers in the EPA Alternative Cover Assessment Program.

A.1.1 Conventional and Evapotranspiration Covers

Conventional cover designs are multilayered systems that typically include an erosion protection layer over a soil-rooting medium (Figure A-1). These layers are underlain by a synthetic membrane barrier and a 2-foot thick compacted clay layer to prevent moisture from infiltrating into the waste. At the RFETS Present Landfill, the compacted clay would be underlain by an interim cover, as shown in the modeled profile in Figure A-1.

The alternative ET cover proposed for the Present Landfill will also be a multilayered system (Figure A-1). However, rather than relying on synthetic components that may degrade over time, the ET cover seeks to minimize infiltration by maximizing the ET processes in the soil-rooting medium layer. In addition, conventional covers are susceptible to erosion due to increased runoff, making erosion a major threat to long-term performance. The ET cover is therefore also designed to minimize erosion by incorporation of an erosion protection layer up to 12 inches thick (30 centimeters [cm]) at the surface.

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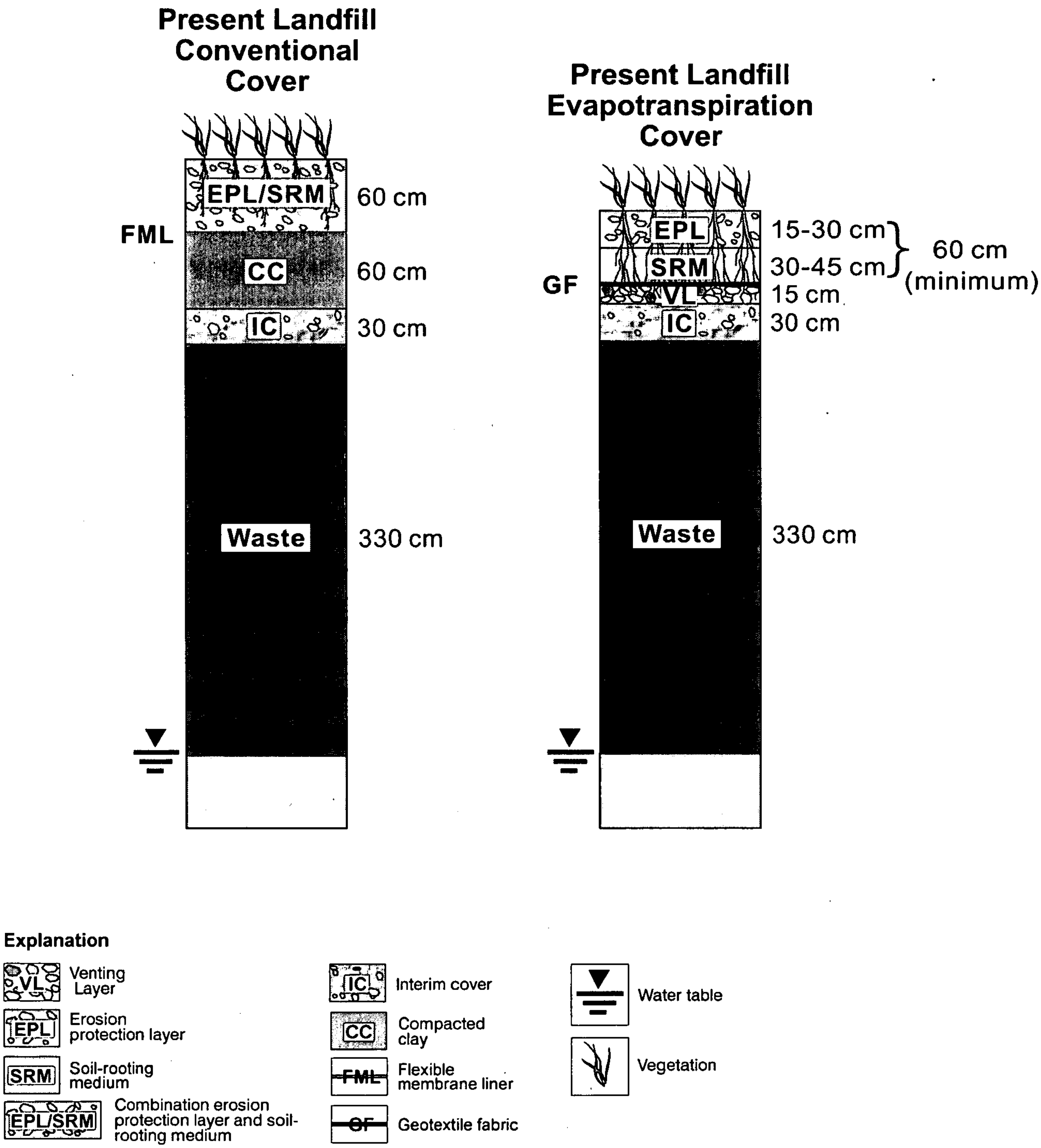

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Modeled Cover Cross-Sections

Figure A-1

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The alternative cover proposed at the RFETS use soil as a sponge to store rainfall until evaporation and plant transpiration dry the soil out again. The soil in this cover serves the same role as it does in the natural ecosystem or in a farmer's field. In these systems, stored water in the soil from summer rainfalls is typically removed rapidly, while stored water from winter precipitation typically increases until spring.

Several soil parameters affect the amount of water that can be stored and removed from an alternative cover. For example:

- *Thickness:* A thicker layer of soil can be used to store more water.
- *Texture:* Finer-textured soils generally hold more water than coarser, sandy soils.
- *Root density:* If roots are not present, less water can be removed from the soil.

A numerical model is needed to evaluate the potential effectiveness of various combinations of soil types, soil thicknesses, and soil layers in a landfill cover.

In the alternative cover cross-section, the erosion protection and soil-rooting medium layers will be separate layers with a combined thickness of at least 2 feet (60 cm) (Figure A-1). The erosion protection layer and soil-rooting medium thicknesses may vary depending upon anticipated erosion rates. The erosion protection layer will vary from a minimum of 6 inches up to 12 inches, depending upon the degree of erosion protection needed, and an additional 18 inches of soil will be added to provide a 2-foot minimum cross section. This will ensure an adequate soil thickness for evapotranspiration in the face of erosional losses over the next millennium.

Below the soil-rooting medium will be a soil-venting layer, which will provide oxygen to the root systems to maintain transpiration of water from the cover profile. This layer will be at least 6 inches (15 cm) thick. In addition, grade fill will be used, which will result in the average cover thickness being generally thicker than the minimum cover thickness.

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A.1.2 Model Description

Predicting long-term performance of isolating subsurface waste sites with regard to inhibiting contaminant migration requires a model capable of simulating water flow in the unsaturated soils above the waste. The UNSAT-H model is designed for calculating water flow in unsaturated media. The model was developed at Pacific Northwest National Laboratory to assess water dynamics of near-surface, waste disposal sites at the Hanford Site. UNSAT-H 3.0 is a FORTRAN computer code that uses a one-dimensional finite element version of Richard's equation to simulate flow of water, vapor, and heat in soils. The code is designed for use in water balance studies and is primarily used to predict deep percolation as a function of such environmental conditions as climate, soil type, and vegetation. The model has been verified against analytical solutions and validated against lysimeter data by Fayer et al. (1992).

The DBS&A modeling was performed using an unmodified version of UNSAT-H 3.0 obtained from the Internet at http://etd.pnl.gov:2080/~mj_fayer/unsath.htm. Full model documentation is also available at the same site. The hydrologic water balance is expressed in the UNSAT-H model according to the following general soil-water budget formula:

$$\Delta S = P - E - T - D \tag{1}$$

where: ΔS = Change in water stored in soil profile

P = Precipitation

E = Evaporation

T = Transpiration

D = Drainage

As discussed in Section 1.1, the ability to store water is key to alternative cover performance. Drainage or percolation is the term calculated in the model by subtracting evaporation, transpiration, runoff, and storage changes from precipitation. For modeling of drainage, mass balance errors should be small. Generally, the modeled runs show mass balance errors on the order of 0.2 cm/year and recharge/discharge values of the same magnitude. Runoff is not explicitly calculated. Instead, the model infiltrates rainfall into the soil profile at a rate based upon hydraulic conductivity and soil-water potential and classifies all the water that does not infiltrate into the profile as runoff. Higher rainfall intensities are more likely to exceed the soil infiltration rate and result in increased runoff.

Vapor flux can be calculated, but not when transpiration is being used in the model. Thus, for normal evapotranspiration covers, UNSAT-H ignores water vapor movement. The factors most affecting evaporation and transpiration are discussed in Section 2.1 and 2.3.1.

UNSAT-H was thoroughly evaluated for modeling alternative landfill cover performance at the nearby RMA, which has similar climate, soils, and vegetation to RFETS, and was also used for design of a large ongoing lysimeter study at the same site. In addition to predicting the water budget, the model predicts daily soil-water content, soil-water potential energy, and water flux rates as a function of soil depth.

At a July 27, 2001 on-site meeting on the alternative cover project, the Department of Energy (DOE), Kaiser Hill, LLC, Colorado Department of Public Health and Environment (CDPHE), and EPA Region VIII concurred with DBS&A's recommendation of UNSAT-H as the model of choice for the RFETS alternative cover (Kaiser-Hill, 2001). UNSAT-H was previously evaluated for modeling alternative landfill cover performance at the nearby RMA and was also used for design of a large ongoing lysimeter study at the same site. CDPHE regulators have also required UNSAT-H equivalency modeling at Fort Carson.

A.2 Input Parameters

Evaporation input to the model is driven by weather data using the Penman equation. Transpiration is based upon the Ritchie equation, which drives transpiration as a function of leaf area index (LAI). Transpiration is also dependent upon rooting distribution in the soil profile and upon soil-water potential. These and other parameters are used as input to UNSAT-H. Some of the parameters are straightforward (such as site elevation and height of the wind velocity measurements) or have standard values. The more important site-specific parameters, such as the climatological, soil, and vegetative parameters and/or data inputs, are discussed in Sections

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2.1 through 2.3. Table A-1 summarizes the sources of data input into UNSAT-H for modeling the ET cover.

Table A-1. Sources of UNSAT-H Climatological, Vegetation, and Soil Parameters

Input Parameter	Source
Climatological Data	
Precipitation	Denver Stapleton Airport National Climatic Data Center (NCDC) primary weather station (WBAN #23062)
Temperature	Denver Stapleton Airport NCDC primary weather station (WBAN #23062)
Dew point	Calculated from temperature and relative humidity, the latter of which was taken from NCDC primary weather station at Denver, Colorado (WBAN #23062)
Solar radiation	Denver Stapleton Airport NCDC primary weather station (WBAN #23062)
Wind speed	NCDC primary weather station at Denver, Colorado (WBAN #23062)
Cloud cover	NCDC primary weather station at Denver, Colorado (WBAN #23062)
Plant Data	
Leaf area index	Pawnee Grasslands data
Rooting depth	Borrow site observations, soil gas data
Rooting density	Root density function AA=0.8705, B1=0.06108, B2=0.0144 (same parameters as at RMA)
Soil Data	
Cover material hydrologic characteristics	DBS&A laboratory data from LaFarge Quarry sample
Number of layers	Multiple layer systems

WBAN = Weather Bureau, Army, and Navy RMA = Rocky Mountain Arsenal

A.2.1 Weather

Nearly complete climatological data are available from the Denver Stapleton Airport, where such data have been collected since the late 1940s. Individual precipitation events vary between the airport and the RFETS, but the long-term trends, variability, and averages are similar. Therefore, climatological data from the Denver Stapleton Airport were used as input for UNSAT-H modeling of the RFETS ET cover.

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In order to provide a conservative analysis, the historical conditions most likely to produce recharge through soil covers, that is, years of high precipitation, were selected from the climatological record for the modeling analysis. Two periods for simulation were selected from the 48-year precipitation record at the Denver Stapleton Airport: (1) precipitation during the winter and early spring of 1982 to 1983, which was greater than for any similar period of record, and (2) the wettest one-year, three-year, and five-year periods of record, all of which fall within the 1965 through 1969 period.

Evaporation and transpiration are influenced by wind speed, solar radiation, and relative humidity, and solar radiation is in turn affected by cloud cover and other sun-blocking features. Data from Denver Stapleton Airport will not reflect known differences in wind speed and the decrease in solar radiation due to the proximity of RFETS to the mountains east of Rocky Flats, yet both of these factors affect the water balance calculated by UNSAT-H. The stronger winds found at RFETS will increase evaporation and transpiration, while reduced solar radiation in late afternoons will reduce evaporation and transpiration. Both wind speed and solar radiation interact with slope aspect. The west-facing slopes that may be most affected by reduced evening solar radiation will receive the largest benefit of increased drying from mountain winds.

A small reduction on the order of 1 percent in solar radiation will also occur at RFETS due to the mountains in the west. The average length of daylight at RFETS is slightly greater than 12 hours. The inclination of the mountains to the west is about 4 degrees above the horizon. Thus, approximately 4/180 or about 2 percent of the 12 hours of sunlight is blocked. Because of the lower intensity of evening radiation, less than 2 percent of solar radiation is blocked. In addition, because RFETS itself is on an overall eastern incline, part of the 2 percent loss in solar radiation is compensated for by extra morning radiation. Radiation translates into potential evapotranspiration (PE) in the UNSAT-H 3.0 model (page 4.22 of the manual) as

$$PE = \frac{sR_{ni}}{s+\tau} + \frac{\tau}{s+\tau} \quad 0.27\left(1+\frac{U}{100}\right)(e_a - e_d)$$

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where PE = potential evapotranspiration

s = the slope of the saturation vapor pressure-temperature curve

R_{ni} = the isothermal net radiation

τ = a psychrometric constant

U = a 24-hour wind run (kilometers per day [km/d])

e_a = saturation vapor pressure at the mean air temperature

e_d = the actual vapor pressure

Because PE scales linearly with solar radiation, the loss in PE is on the order of 1 percent.

Because of the proximity of RFETS to the Rocky Mountains, the site experiences stronger winds than does Denver Stapleton Airport, the source of the wind data used in the UNSAT-H analyses. In UNSAT-H, wind speed is used as a daily average. The equation above also shows that PE increases with wind speed (U). While the magnitude of the wind drying effect also depends upon solar radiation and water vapor pressure, more wind will result in more drying at RFETS.

The net effect of stronger winds and reduced solar radiation is considered negligible and was not considered further.

A.2.2 Soil

An investigation was conducted to characterize, sample, and test the typical borrow soil available at RFETS for possible use in constructing the ET cover. Soil was sampled from the LaFarge Quarry adjacent to the northern RFETS boundary, where borrow soil may be obtained during cover construction. Results of the soil testing are summarized in Appendix H of the Conceptual Design Report.

The soil at the LaFarge Quarry was characterized in the DBS&A laboratory as a sandy loam using the USDA soil classification and a clayey sand with gravel using the ASTM soil classification. The calculated porosity of the soil is 38.6 percent by volume. The dry bulk

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density of the material is 1.63 grams per cubic centimeter. The saturated hydraulic conductivity is 5.1 x 10^{-4} centimeters per second (cm/s).

The van Genuchten parameters characterize the relationships among soil-water potential, soil-water content, and unsaturated hydraulic conductivity. These relationships are needed to quantify the dynamics of water movement and storage within a landfill cover profile.

- The parameter α is closely related to the largest pores in a soil. Coarser soils typically have larger pores and larger α's.

- The parameter *N* represents a pore size distribution. A large N (greater than 2) is typical of well sorted sandy soils and indicates that most pores are of similar size. A small N (close to 1) indicates a range of pore sizes in the soil and is more typical of finer-textured soils.

- Residual moisture content is the water content at which liquid water flow ceases in a soil. Soils typically have some water absorbed in clays or on surfaces that does not undergo Darcian flow. A soil albedo value of 0.2 was used for modeling (Houghton, 1985).

- Saturated moisture content is the water content at complete saturation and is equivalent to the total porosity.

The RETC program (van Genuchten et al., 1991) was used to obtain the van Genuchten fitting parameters for UNSAT-H model input. RETC is a computer program used to analyze the soil-water retention and hydraulic conductivity functions of unsaturated soils, both of which are key parameters in any quantitative description of water flow into and through the unsaturated zone of soils. The program uses the parametric models of Brooks-Corey and van Genuchten to represent the soil-water retention curve and the theoretical pore-size distribution models of Mualem and Burdine to predict the unsaturated hydraulic conductivity function from observed soil-water retention data.

The van Genuchten parameters for this sample are:

- $\alpha = 0.0438$
- $N = 1.37$
- Residual moisture content (θ_r) = 0.1100 cubic centimeters per cubic centimeter (cm^3/cm^3)
- Saturated moisture content (θ_s) = 0.3836 cm^3/cm^3

These soil data were input into UNSAT-H using the van Genuchten function model option.

A.2.3 Vegetation

UNSAT-H requires the input of various parameters for use in predicting the amount of evapotranspiration from the soil profile. For vegetation, these include LAI, percentage of bare soil, and root density.

A.2.3.1 Leaf Area Index

One important set of vegetative parameters describes the LAI distribution throughout the year. LAI is the ratio of leaf area to land area; one square meter of leaves per square meter of land surface gives an LAI of 1.0. The LAI input into UNSAT-H was based on the short grass prairie LAIs developed at Pawnee National Grasslands and previously used at RMA. The ET cover modeling scenarios assumed a standard annual distribution of LAI (Figure A-2) and did not consider the initial several seasons of reduced LAI while vegetation is being established on the cover. The number of seasons until a vegetative cover is fully established will depend upon the weather during establishment.

UNSAT-H linearly interpolates between dates where the LAI is specified by the user. Dates for the last frost in the spring and the first frost in the fall were used along with other site-specific knowledge to establish the growing season at RFETS.

Prairie fires were also considered for their effects on the performance of cover vegetation. However, little evidence has been found to relate fire intensity to killing of perennial prairie grass stands or vegetative production (Bidwell and Engle, 1992). Prairie fires are high-intensity short-duration fires that do not kill root systems. Perennial prairie plants have coevolved with fire, and

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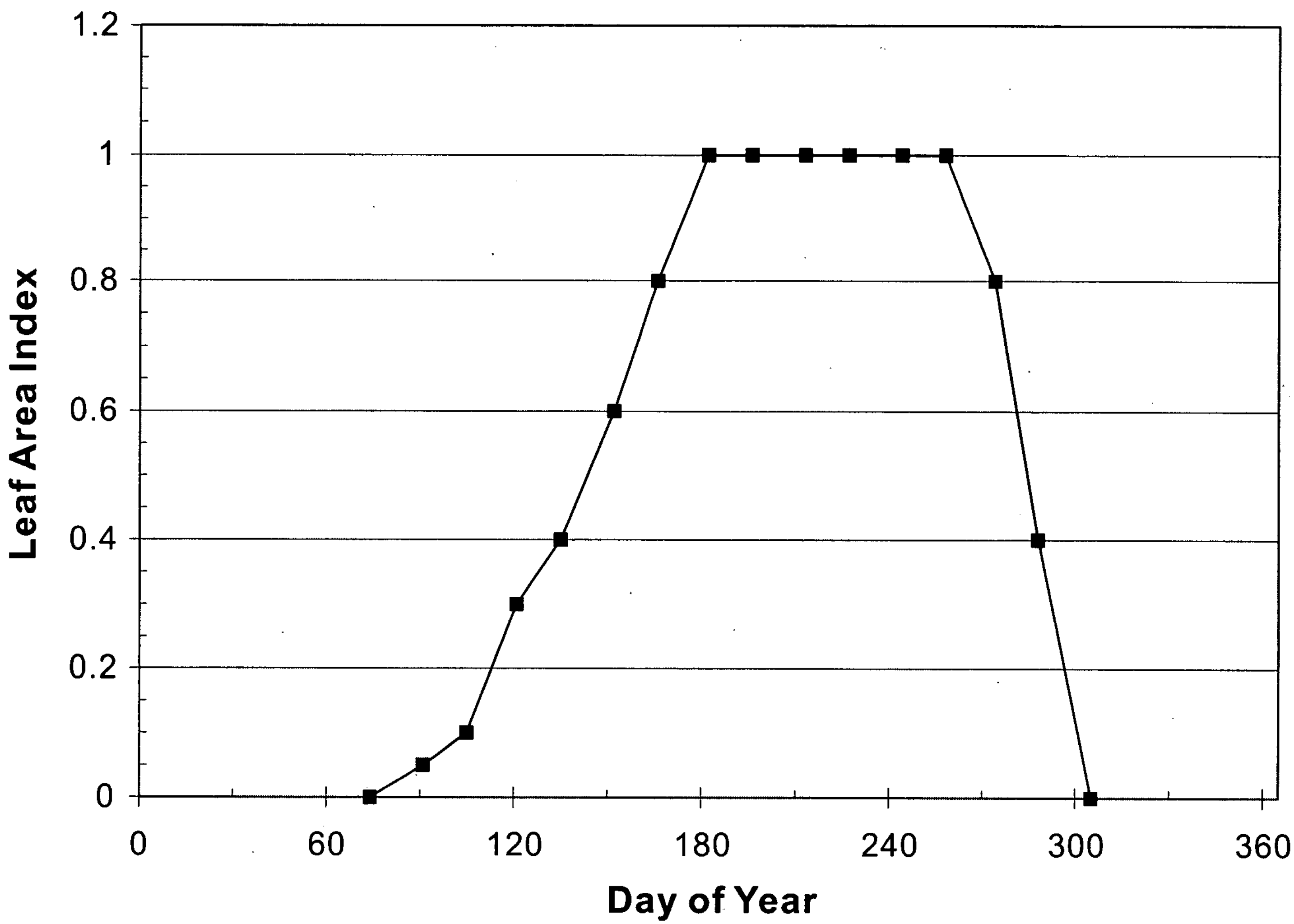

Explanation

Denver area leaf area index measurement

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Leaf Area Index

Figure A-2

Agropyron, a common prairie plant genus, even derives its name from this association (from *agro* for field or soil and *pyr* for fire). Indeed, fire is a commonly used rangeland management tool to restore damaged or overgrazed lands.

A.2.3.2 Percentage of Vegetation-Free Patches

Areas without vegetation undergo evaporation but not transpiration. Based on studies conducted at the RMA in Denver, the average percentage of bare patches for cool-season- and warm-season-dominated grassland areas are 5 percent and 2 percent, respectively (Morrison Knudsen, 1989). The higher value, 5 percent, was used for input to UNSAT-H in the RFETS scenarios. This value is consistent with observations of vegetation at RFETS, where vegetation-free areas are small (less than 1 meter in diameter) except for paths and trails.

The term "bare soil" as used in the model can lead to confusion with other parameters. Kulakow (2001) divided the alternative cover test plot surface at RMA into "bare ground," plant litter, and living plant material. These terms are applied on the scale of centimeters. The "bare soil" parameter as used in UNSAT-H refers to patches on the scale of meters where root water uptake is absent and only evaporation is active. To confirm this interpretation, the bare soil parameter was changed from 5 percent to both 0 percent and 100 percent. Transpiration in these runs dropped to zero at 100 percent bare area (i.e., no plants). Transpiration increased about 2 percent when bare area was reduced from 5 percent to 0 percent. Evaporation partially offset the lack of transpiration on the bare area.

A.2.3.3 Root Density

UNSAT-H requires three parameters to describe the root density function. These parameters were determined by fitting an exponential curve (used by UNSAT-H) to data reported by Liang et al. (1989) for a grassland vegetation on clay/loam soils at the Pawnee Grasslands in northern Colorado (Figure A-3). The three parameters are AA = 0.8705, B1 = 0.06108, and B2 = 0.0144. For perspective, these coefficients cause UNSAT-H to calculate that 80 percent of the root length is in the upper 1 foot of soil. This root density function is considered reasonable for a well developed vegetative cover of the type proposed at RMA (Redente, E., personal communication with George Chadwick [DBS&A], April 17, 1997), which is similar to the

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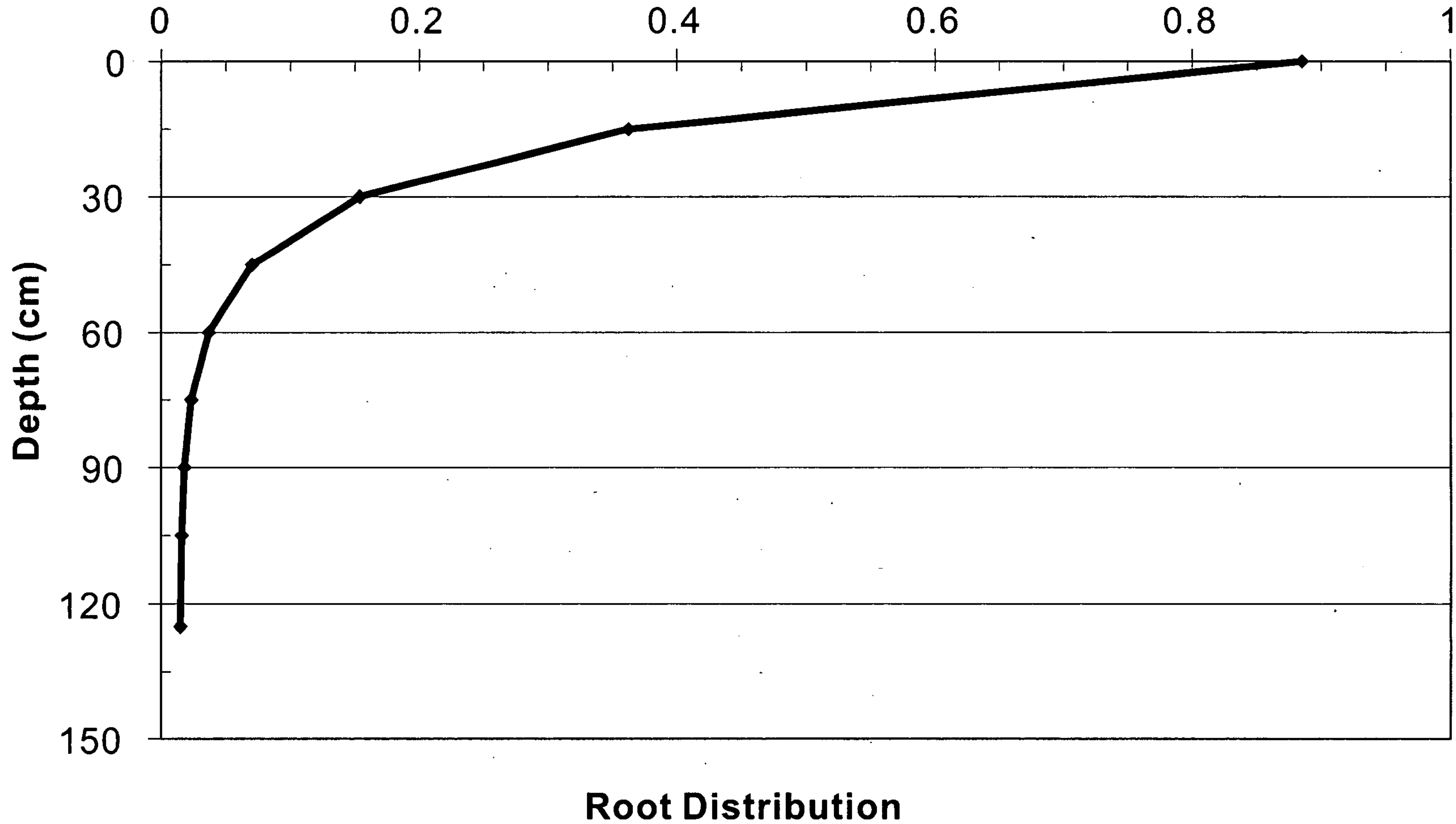

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Root Density Function

Figure A-3

proposed RFETS Present Landfill ET cover. DBS&A requested input from the KH Ecology Group to verify that the root density function was reasonable for use at the RFETS (Table A-2).

The specified maximum rooting depth was set equal to the thickness of the cover being modeled. Rooting depths in the borrow material area near the RFETS were observed to reach depths deeper than the cover thicknesses likely to be proposed (6 feet [180 cm] and 5 feet [150 cm]). Several local soil surveys also report rooting depths of 5 feet (150 cm) or greater.

Initially, the suction head corresponding to the water content below which plants wilt and stop transpiring (HW in UNSAT-H) is set at 20,000 centimeters (cm) (approximately 20 bar). The suction head corresponding to the water content below which plant transpiration starts to decrease, sometimes referred to as the root-soil water potential inflection point (HD in UNSAT-H), is set at 3,000 cm based on information presented by Gardner (1983) for loamy soils. The suction head corresponding to water content above which plants do not transpire because of anaerobic conditions (HN in UNSAT-H) is set at –1 cm of water potential.

A.3 Present Landfill Modeling

UNSAT-H can simulate one-dimensional soil systems made up of multiple layers with differing physical characteristics. The Present Landfill ET cover will be a multilayered system (Figure A-1) with the major component being a rooting medium soil layer consisting of borrow material with the characteristics described in Section 2.2, that is, a loamy soil with gravel.

The surface boundary in the ET cover model was specified as a flux boundary for all simulations, while the bottom boundary for all simulations was specified as a water table boundary. Tradeoffs in program control variables are necessary to optimize solution accuracy and computer time, and the guidelines recommended by Fayer (2000) were used to determine the nodal spacing. Near the surface, the nodal spacing was small (0.1 cm) to avoid numerical instabilities caused by rapid change in suction heads due to evaporation, transpiration, and precipitation. Reduced nodal spacings were also used at boundaries within a soil cover profile, again to reduce the potential for numerical instability within the modeled soil profile.

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Table A-2. Root Depths for Various Grasses and Forbs Rocky Flats Environmental Technology Site

Common Name	Maximum Depth (in feet)	Working Depth (in feet)	Lateral Spread (in feet)
Grasses			
Junegrass	1.8 – 2.2	1.2 – 1.3	About 0.7
Little Bluestem	3.5 – 8.0	3.0 – 6.7	1.2 – 3.0
Blue Grama	2.3 – 4.3	1.7 – 3.6	0.3 – 2.1
Buffalo Grass	4.5 – 7.2	3.0 – 5.0	0.8 – 1.7
Quackgrass	8	6	very little, mostly straight down
Big Bluestem	9.3	5	0.7 – 1.2
Side Oats Grama	5.5	4.0 – 4.5	0.7 – 1.5
Switchgrass	9.2	7	0.3
Kentucky Bluegrass	7	3.3	0.3 – 0.5
Red Threeawn	2.3 – 4.3	2.0 – 3.0	0.4 – 0.7
Sand Dropseed	1.8	1.3	1.5 – 1.7
Hairy Grama	3.3	1.7	1.0 – 1.5
Needle and Thread Grass	2.9 – 5.0	2.5 – 3.5	0.8 – 1.5
Green Needlegrass	11.7	8.0 – 9.0	1.0 – 1.5
Smooth Brome	3.0 – 3.4	2.3	NA
Orchard Grass	2.8 – 3.1	2.2 – 2.3	NA
Intermediate Wheatgrass	7.2 – 9.0	5.5 – 7.0	0.7
Forbs			
Curly–top Gumweed	6.1	3.3	0.3 – 0.8
Blazing Star	15.8	6.0 – 10.0	usually no surface absorbing laterals
White Sweetclover	1.3 – 6.5	1.3 – 5.8	0.3
Wild Alfalfa	9	6	little absorption in first 2 ft. of soil
Wild Rose	21.2	16	little surface absorption
Golden Aster	6.9 – 13.0	5.5 – 10.0	0.7 – 2.0
Prairie Coneflower	2	2	0.5 – 1.0
Silver Sage	6.0 – 7.8	3.0 – 4.0	0.7 – 1.0
Snakeweed	6.5	4.4	2
Yucca	7	2	20 – 30

Notes: Prepared by Jody Nelson based on information from Weaver (1920).
Data represent the range of values found for these species under varying soil and other environmental conditions.

The van Genuchten fitting parameters for the erosion protection layer, soil-rooting medium, and the interim cover layer were adjusted (Table A-3) to reflect the loss of water-holding capacity caused by the presence of gravel and cobbles in the available soil. The water-holding capacity values for the erosion protection layer are 83 percent by volume of the values for the soil-rooting medium, which is equal to 25 percent coarse material by weight. A 25 percent (by mass) coarse admixture is typical of erosion protection layers. The values of the interim soil cover materials are also 83 percent by volume of the soil-rooting medium.

Hourly weather records from the Denver Stapleton Airport were used to develop the precipitation portion of the input files. For each simulation, the sequential weather data for 1982, 1982, 1983 were run sequentially three times (for a total of 9 years) to allow the initial soil-water conditions in the model domain to attain a steady state with respect to typical climatic conditions, and the period 1965 through 1969 was repeated six times to achieve a wet 30-year simulation. In these modeling runs, nearly all water was allowed to infiltrate into the soil profile with virtually no runoff. The combination of nearly eliminating runoff and using a wet weather period for modeling increases the confidence that the cover thicknesses suggested by the modeling results are conservative.

A.4 Modeling Results

Attachment A1 presents the results of each Present Landfill run. Each run is represented by four graphs showing (1) mass balance error, (2) recharge or discharge, (3) a summary of each year's water balance, and (4) the dynamics of the 5-year water balance.

Sensitivity studies were conducted to determine how well a potential cover cross section would meet design needs. In the model, infiltration represents the flux into the top surface of the model domain. Drainage represents recharge to the water table beneath the waste material. Once meteoric water enters the model domain as infiltration, it is redistributed across nodes by evaporation, transpiration, or drainage. Water can be lost through the top surface by evaporation and transpiration. Water can also move downward and eventually out of the model domain by drainage.

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Table A-3. Hydrologic Parameters Used in UNSAT-H for Present Landfill Model

Location	Description	K_{sat}		Volumetric Water Content (cm^3/cm^3)		α	N
		(cm/s)	(cm/hr)	θ_s	θ_r	(cm^{-1})	(dimensionless)
Present Landfill prescriptive cover	Erosion protection/soil rooting medium layer	1.0×10^{-5}	0.036	0.32	0.09	0.0438	1.37
	Flexible membrane liner	2.0×10^{-13}	7.2×10^{-10}	0.005	0.00	0.0500	2.00
	Compacted clay	1.0×10^{-7}	0.0004	0.30	0.00	0.0020	1.15
	Interim cover	4.2×10^{-4}	1.512	0.32	0.09	0.0438	1.37
	Waste	1.05×10^{-4}	0.3780	0.08	0.02	0.0438	1.37
Present Landfill evapotranspiration cover	Erosion protection layer	4.2×10^{-4}	1.512	0.32	0.09	0.0438	1.37
	Soil rooting medium	5.1×10^{-4}	1.836	0.38	0.11	0.0438	1.37
	Interim cover	4.2×10^{-4}	1.512	0.32	0.09	0.0438	1.37
	Waste	1.05×10^{-4}	0.3780	0.08	0.02	0.0438	1.37

K_{sat} = Saturated hydraulic conductivity
cm^3/cm^3 = Cubic centimeters per cubic centimeter
cm/s = Centimeters per second
cm/hr = Centimeters per hour

θ_s = Saturated moisture content
θ_r = Residential moisture content
α = Fitting parameter
N = Fitting parameter

The graphs of initial water flow through the cross sections in early modeling years show that the magnitude and direction of water flow is dominated by the initial soil conditions set for modeling (Attachment A1). Because unsaturated flow is slow in the lower sections of the landfill cover profiles, it takes several years for flux magnitude and direction to stabilize. Typically, by the tenth year of modeling the system has reached a steady state of discharge or recharge as shown on the flux graphs for a given cover profile. This steady state is seen in the 5-year repeating values of percolation that correspond to the repeating 5 years of weather data used.

Mass balance error graphs are shown as a standard check on landfill cover design runs where desired maximum cover percolation is a small fraction of the water balance (typically on the order of 1 percent). All runs show low mass balance errors (Attachment A1). For example, 15 inches of rainfall (45 cm) falls at RFETS annually. Recharge of 1 percent would represent a flux of 0.45 centimeter per year (cm/yr). While there is no absolute numerical standard for either mass balance error or for percolation performance, mass balance errors in this modeling study are typically on the order of 0.025 cm/yr, and the highest percolation rate modeled in a proposed cross section is about 0.3 cm/yr.

Mass balance errors are dependent upon several factors. The factors showing the most sensitivity in these runs are individual precipitation events. Large precipitation events tend to result in an increase in mass balance errors. This general pattern is shown across the mass balance error figures with lower mass balance errors in the drier years at the beginning of the model runs and a repeating pattern of increased mass balance errors in later years, driven by the higher precipitation data and the repeating 5-year data set.

Recharge or discharge graphs are also shown for each run (Attachment A1). Discharge is simply upward flow or negative recharge or negative percolation. Discharge is common in semiarid and arid locations with shallow water tables. Plant roots can extract water from the water table or from precipitation. Cover design can change the magnitude of recharge and tip the balance between recharge and discharge.

A bar graph summarizing the annual water balance is also provided for each run (Attachment A1). These graphs are a convenient way to assess the relative importance of each water

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balance component for each year's weather. For example, the relative importance of evaporation versus transpiration can be assessed for a given cover type or rooting depth. Such internal comparisons of analyses provide one important assessment of the general quality of model results.

The final graph in each run shows the daily dynamics of the water balance across the repeating 5-year period (Attachment A1). This graph allows the reader to see the fate of water from a given precipitation event as it is partitioned into storage, evaporation, and transpiration. Water stored in the soil increases during winter, while ET decreases. Stored water is then transpired in spring and summer. The main caveat for interpretation is that runoff has intentionally been numerically minimized by controlling rainfall intensities for conservative design evaluation, and wet years have been run. Thus, the results are not representative of typical performance, but more accurately reflect cover performance under stressed and wet conditions.

A.4.1 Scenario 1: Total Evapotranspiration Cover Thickness

At each site, the first objective of the modeling was to determine how thick the cover must be to perform its functions. For numerical modeling of the Present Landfill, a combination of an erosion protection layer and a soil-rooting medium was placed over the existing profile at the site. In addition, a 6-inch (15-cm) methane-venting layer was included. For sensitivity testing (to evaluate potential percolation), the initial 2-foot (60-cm) thickness of the soil-rooting medium was decreased in 6-inch (15-cm) increments in each subsequent run until the soil-rooting medium was reduced to zero thickness.

The results of the water balance modeling with UNSAT-H for the vegetated ET cover on the Present Landfill are shown in Table 4. The results of the last 5 years (which correspond to 1965 through 1969) of a 30-year simulation were averaged for each run.

As shown in Table A-4, the UNSAT-H model predicted no runoff for the Present Landfill ET cover. The soil-rooting medium depth was varied in Runs 1 and 10 through 13 (Attachment A1) to determine how the ET cover will provide for equivalent infiltration reduction performance. These runs all used 30 cm (1 foot) of soil erosion protection medium. The drainage changed

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Table A-4. Modeling Results for Present Landfill Evapotranspiration Cover
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Run	Input Parameters[a] (cm)	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
1	RD = 120	1965	55.55	55.55	0.00	24.37	34.25	–0.11	0.24
	CT = 120	1966	27.46	27.46	0.00	14.34	15.10	–0.11	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.95	31.39	–0.11	0.28
	SRM = 60	1968	30.81	30.81	0.00	17.34	15.44	–0.11	0.23
	IC = 30	1969	54.66	54.64	0.02	21.64	28.26	–0.11	0.14
Average of last 5 years		NA		45.53	0.00	20.53	24.89	–0.11	0.22
2	RD = 105	1965	55.55	55.55	0.00	24.29	34.37	–0.11	0.24
	CT = 120	1966	27.46	27.46	0.00	14.30	15.17	–0.11	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.83	31.55	–0.11	0.29
	SRM = 60	1968	30.81	30.81	0.00	17.29	15.44	–0.11	0.23
	IC = 30	1969	54.66	54.66	0.00	21.57	28.18	–0.11	0.19
Average of last 5 years		NA		45.54	0.00	20.46	24.94	–0.11	0.23
3	RD = 90	1965	55.55	55.55	0.00	24.27	34.06	–0.07	0.24
	CT = 120	1966	27.46	27.46	0.00	14.25	15.69	–0.06	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.72	31.40	–0.06	0.29
	SRM = 60	1968	30.81	30.81	0.00	17.25	15.83	–0.07	0.23
	IC = 30	1969	54.66	54.66	0.00	21.52	27.84	–0.07	0.19
Average of last 5 years		NA		45.54	0.00	20.40	24.96	–0.07	0.23
4	RD = 75	1965	55.55	55.55	0.00	24.31	33.62	0.00	0.24
	CT = 120	1966	27.46	27.46	0.00	14.21	16.05	0.04	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.64	31.10	0.03	0.29
	SRM = 60	1968	30.81	30.81	0.00	17.22	16.23	0.00	0.22
	IC = 30	1969	54.66	54.66	0.00	21.53	27.57	0.00	0.19
Average of last 5 years		NA		45.54	0.00	20.38	24.91	0.01	0.23

[a] RD = Rooting depth
CT = Cover thickness
EPL = Erosion protection layer
SRM = Soil-rooting medium
IC = Interim cover
VL = Venting layer
cm = Centimeter
NA = Not applicable

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Table A-4. Modeling Results for Present Landfill Evapotranspiration Cover
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Run	Input Parameters [a] (cm)	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
5	RD = 60	1965	55.55	55.55	0.00	24.33	32.81	0.20	0.24
	CT = 120	1966	27.46	27.46	0.00	14.27	16.35	0.36	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.50	30.69	0.20	0.29
	SRM = 60	1968	30.81	30.81	0.00	17.24	16.46	0.17	0.23
	IC = 30	1969	54.66	54.66	0.00	21.55	27.28	0.11	0.19
Average of last 5 years		NA		45.54	0.00	20.38	24.72	0.21	0.23
6	RD = 45	1965	55.55	55.55	0.00	24.36	32.25	0.55	0.11
	CT = 120	1966	27.46	27.46	0.00	14.38	16.39	0.77	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.38	30.36	0.30	0.28
	SRM = 60	1968	30.81	30.81	0.00	17.31	16.44	0.36	0.23
	IC = 30	1969	54.66	54.66	0.00	21.54	27.02	0.23	0.19
Average of last 5 years		NA		45.54	0.00	20.39	24.49	0.44	0.21
7	RD = 30	1965	55.55	55.55	0.00	24.25	30.60	2.68	0.24
	CT = 120	1966	27.46	27.46	0.00	14.42	15.99	1.43	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.12	29.47	0.85	0.28
	SRM = 60	1968	30.81	30.81	0.00	17.34	15.92	1.11	0.23
	IC = 30	1969	54.66	54.66	0.00	21.53	25.76	1.09	0.18
Average of last 5 years		NA		45.54	0.00	20.33	23.54	1.43	0.23
8	RD = 15	1965	55.55	55.55	0.00	23.74	27.76	6.39	0.22
	CT = 120	1966	27.46	27.46	0.00	14.05	15.87	1.73	0.21
	EPL = 30	1967	59.21	59.21	0.00	23.45	27.69	3.80	0.28
	SRM = 60	1968	30.81	30.81	0.00	16.98	15.48	1.32	0.22
	IC = 30	1969	54.66	54.66	0.00	20.94	23.38	4.04	0.17
Average of last 5 years		NA		45.54	0.00	19.83	22.04	3.46	0.22

[a] RD = Rooting depth
CT = Cover thickness
EPL = Erosion protection layer
SRM = Soil-rooting medium
IC = Interim cover
VL = Venting layer
cm = Centimeter
NA = Not applicable

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Table A-4. Modeling Results for Present Landfill Evapotranspiration Cover
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Run	Input Parameters[a] (cm)	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
9	RD = 0	1965	55.55	55.55	0.00	38.57	0.00	18.06	0.13
	CT = 120	1966	27.46	27.46	0.00	27.35	0.00	2.85	0.15
	EPL = 30	1967	59.21	59.21	0.00	40.04	0.00	16.28	0.14
	SRM = 60	1968	30.81	30.81	0.00	29.53	0.00	2.61	0.15
	IC = 30	1969	54.66	54.66	0.00	33.94	0.00	17.80	0.10
Average of last 5 years		NA		45.54	0.00	33.89	0.00	11.52	0.13
10	RD = 105	1965	55.55	55.53	0.02	24.32	34.45	–0.11	0.19
	CT = 105	1966	27.46	27.46	0.00	14.29	15.03	–0.11	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.90	31.57	–0.11	0.28
	SRM = 45	1968	30.81	30.81	0.00	17.29	15.35	–0.11	0.23
	IC = 30	1969	54.66	54.66	0.00	21.61	28.22	–0.11	0.19
Average of last 5 years		NA		45.53	0.00	20.48	24.92	–0.11	0.22
11	RD = 90	1965	55.55	55.55	0.00	24.34	34.23	–0.06	0.24
	CT = 90	1966	27.46	27.46	0.00	14.24	15.19	–0.04	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.89	31.54	–0.06	0.11
	SRM = 30	1968	30.81	30.81	0.00	17.25	15.57	–0.07	0.22
	IC = 30	1969	54.66	54.66	0.00	21.59	28.14	–0.07	0.19
Average of last 5 years		NA		45.54	0.00	20.46	24.93	–0.06	0.20
12	RD = 75	1965	55.55	55.55	0.00	24.42	33.89	0.17	0.24
	CT = 75	1966	27.46	27.46	0.00	14.20	15.07	0.11	0.22
	EPL = 30	1967	59.21	59.21	0.00	24.83	31.42	0.02	0.29
	SRM = 15	1968	30.81	30.81	0.00	17.20	15.43	0.05	0.23
	IC = 30	1969	54.66	54.66	0.00	21.68	28.03	0.03	0.19
Average of last 5 years		NA		45.54	0.00	20.46	24.77	0.08	0.23

[a] RD = Rooting depth
CT = Cover thickness
EPL = Erosion protection layer
SRM = Soil-rooting medium
IC = Interim cover
VL = Venting layer
cm = Centimeter
NA = Not applicable

Table A-4. Modeling Results for Present Landfill Evapotranspiration Cover

Run	Input Parameters[a] (cm)	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
13	RD = 60	1965	55.55	55.55	0.00	24.61	33.11	0.67	0.24
	CT = 60	1966	27.46	27.46	0.00	14.13	14.71	0.40	0.23
	EPL = 30	1967	59.21	59.21	0.00	24.96	30.53	0.50	0.28
	SRM = 0	1968	30.81	30.81	0.00	17.16	15.26	0.47	0.23
	IC = 30	1969	54.66	54.66	0.00	21.82	26.86	1.33	0.19
Average of last 5 years		NA		45.54	0.00	20.54	24.09	0.67	0.23
14	RD = 90	1965	55.55	55.55	0.00	24.60	34.36	−0.07	0.24
	CT = 90	1966	27.46	27.46	0.00	14.75	14.36	−0.07	0.22
	EPL = 15	1967	59.21	59.21	0.00	25.25	31.28	−0.07	0.29
	SRM = 45	1968	30.81	30.81	0.00	17.37	15.21	−0.07	0.24
	IC = 30	1969	54.66	54.66	0.00	21.55	28.14	−0.07	0.20
Average of last 5 years		NA		45.54	0.00	20.70	24.67	−0.07	0.24
15	RD = 75	1965	55.55	55.55	0.00	24.69	33.98	0.44	0.23
	CT = 105	1966	27.46	27.46	0.00	14.20	14.20	0.32	0.21
	EPL = 30	1967	59.21	59.21	0.00	25.18	31.23	0.20	0.27
	SRM = 30 VL = 15	1968	30.81	30.81	0.00	17.19	14.73	0.23	0.22
	IC = 30	1969	54.66	54.66	0.00	21.92	27.86	0.24	0.17
Average of last 5 years		NA		45.54	0.00	20.64	24.40	0.29	0.22
16	RD = 75	1965	55.55	55.55	0.00	24.91	33.96	0.17	0.23
	CT = 105	1966	27.46	27.46	0.00	14.70	13.64	0.17	0.21
	EPL = 15	1967	59.21	59.21	0.00	25.47	31.27	0.12	0.28
	SRM = 45 VL = 15	1968	30.81	30.81	0.00	17.33	14.63	0.11	0.22
	IC = 30	1969	54.66	54.66	0.00	21.91	28.03	0.11	0.19
Average of last 5 years		NA		45.54	0.00	20.86	24.31	0.14	0.23

[a] RD = Rooting depth
CT = Cover thickness
EPL = Erosion protection layer
SRM = Soil-rooting medium
IC = Interim cover
VL = Venting layer
cm = Centimeter
NA = Not applicable

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Table A-4. Modeling Results for Present Landfill Evapotranspiration Cover

Run	Input Parameters[a] (cm)	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
17	RD = 105 CT = 105 EPL = 30 SRM = 30 VL = 15 IC = 30	1965	55.55	55.55	0.00	24.92	33.79	–0.11	0.22
		1966	27.46	27.46	0.00	14.31	14.21	–0.11	0.22
		1967	59.21	59.21	0.00	25.47	31.55	–0.11	0.27
		1968	30.81	30.81	0.00	17.30	14.79	–0.11	0.23
		1969	54.66	54.66	0.00	22.12	28.62	–0.11	0.18
Average of last 5 years			NA	45.54	0.00	20.82	24.59	–0.11	0.22
18	RD = 105 CT = 105 EPL = 15 SRM = 45 VL = 15 IC = 30	1965	55.55	55.55	0.00	25.11	33.75	–0.11	0.23
		1966	27.46	27.46	0.00	14.81	13.64	–0.11	0.22
		1967	59.21	59.21	0.00	25.75	31.34	–0.11	0.27
		1968	30.81	30.81	0.00	17.42	14.61	–0.11	0.23
		1969	54.66	54.66	0.00	22.10	28.49	–0.11	0.19
Average of last 5 years			NA	45.54	0.00	21.04	24.37	–0.11	0.23
20	RD = 15	1965	55.55	55.55	0.00	24.00	27.45	6.38	0.23
	CT = 120	1966	27.46	27.46	0.00	14.45	15.62	1.77	0.22
	EPL = 15	1967	59.21	59.21	0.00	23.87	27.60	3.33	0.28
	SRM = 75	1968	30.81	30.81	0.00	17.13	15.33	1.35	0.23
	IC = 30	1969	54.66	54.66	0.00	21.03	23.26	3.94	0.19
Average of last 5 Years			NA	45.54	0.00	20.10	21.85	3.35	0.23

[a] RD = Rooting depth
CT = Cover thickness
EPL = Erosion protection layer
SRM = Soil-rooting medium
IC = Interim cover
VL = Venting layer
cm = Centimeter
NA = Not applicable

from –0.11 centimeter per year (cm/yr) (upward flux) with a 36-inch-thick (90-cm) cover thickness to +0.67 cm/yr (downward flux) with only a 12-inch-thick (30-cm) erosion protection layer. The model runs are internally consistent and suggest that downward flux occurs with a cover of approximately 50 cm or less. Results from Runs 1 and 10 through 13 are summarized in Figure A1-4 of Attachment A1. Throughout all of the simulations for the Present Landfill ET cover, the mass balance error was never larger than 0.24 cm/yr (Table A-4).

A.4.2 Scenario 2: Rooting Depth

Methane is present in the interim cover at the Present Landfill and affects plant transpiration through displacement of oxygen and concurrent microbial consumption of oxygen and methane, which restricts root growth. Figure A1-8 in Attachment A1 shows two cross section lines (E-E' and F-F') where the major gases carbon dioxide, methane, and oxygen were measured at 1-foot (30-cm) intervals from 1 foot to 7 feet (30 to 210 cm) below ground surface. As shown on the map, the transects intercepted two patches of sparse vegetation and one patch of dense vegetation.

Sparse vegetation is shown on Figure A1-9, while sparse to dense vegetation is shown in Figure A1-10. The x scale starts at 0 percent gas for each location, and each tick mark represents 10 percent gas by volume. The E-E' transect samples were all collected from locations with sparse vegetation (STA 280 on Figure A1-8 is the location of a vent well). Observations of rooting at 400 feet and 455 feet showed moderate rooting density to approximately 4 inches (10 cm) and sparse rooting density to approximately 1 foot (30 cm) deep. The F-F' transect intercepted patches of dense and sparse vegetation. Examination of the data shows that dense vegetation was present only where significant free oxygen concentrations are found below 3 feet (90 cm) in depth. Most of the sparse vegetation locations show diminished oxygen levels even at 1 foot (30 cm) deep.

Because methane inhibits root growth and transpiration, the consequences of a reduced rooting depth were evaluated. Rooting depths were sequentially reduced by 6-inch (15-cm) increments, and the effects on plant transpiration and percolation were evaluated.

In the simulations for the changing rooting depths with no venting layer and no soil gas (Runs 1 through 9, shown on Figures A1-11 through A1-14 and A1-31 through A1-62), the drainage changed from a rate of –0.11 cm/yr (upward) to 11.52 cm/yr (downward) as summarized from the runs in Figure A1-5. As shown in Figure A1-6, the transpiration rate was 24.89 cm/yr with roots to the bottom of the cover and decreased to zero transpiration with no roots present. This result demonstrates the effect of the rooting depth on ET from the soil profile. Transpiration peaks out at about 45 cm, which is consistent with the calculations of approximately zero recharge with a 50-cm-thick cover.

Because of the soil gas results and the rooting observations, the efficacy of a 6-inch-thick (15-cm) landfill gas venting system to reduce adverse impacts of soil gas on the rooting depth was numerically evaluated. Such a venting system will consist of a layer of gravel, cobbles, or other approved material layer (minimum diameter of [1.25 cm]) with a minimum layer thickness of (15 cm) overlain by a geosynthetic fabric layer to prevent soil intrusion. The properties used for the venting layer are from Carsel and Parrish (1988):

- Saturated hydraulic conductivity = 29.7 cm/hr
- Saturated moisture content (θ_s) = 0.43 cm^3/cm^3
- Residual moisture content (θ_r) = 0.045 cm^3/cm^3
- $\alpha = 0.145$
- N = 2.68

Four alternatives were modeled:

- *Alternative 1:* A cross section with a 15-cm (6-inch) erosion protection layer, 45-cm (18-inch) soil-rooting medium, a geosynthetic fabric, 15-cm (6-inch) venting layer, and roots growing to the bottom of the venting layer

- *Alternative 2:* A cross section with a 30-cm (12-inch) erosion protection layer, 30-cm (12-inch) soil-rooting medium, 15-cm (6-inch) venting layer, and roots growing to the bottom of the venting layer

- *Alternative 3:* The same cross section as Alternative 1, except roots grow to 105 cm (42 inches) deep

- Alternative 4: The same cross section as Alternative 2, except roots grow to 105 cm (42 inches) deep

Alternatives 3 and 4 represent the deeper rooting depth that will occur after methane production in the landfill abates.

The geofabric must function until methane generation abates and normal oxygen diffusion can provide oxygen to the root systems. Soil gas calculations (shown in Appendix E of the Conceptual Design Report) suggest that methane production in the Present Landfill will diminish to low levels within 25 to 75 years, as the waste completely degrades. With time, oxygen will penetrate below the soil-venting layer, allowing deeper root growth and improved long-term percolation performance.

The effects of landfill gas on cover performance is summarized in Attachment A1, Figure A1-7, which shows that, if the assumption is made that no methane is present (no methane, no vent layer), the cover will discharge approximately 0.06 to 0.075 cm/yr. If the effect of landfill gas on performance is modeled (methane, no vent layer), estimated percolation is approximately 3.0 to 3.5 cm/yr, which on a 20-acre footprint represents a seepage rate of approximately 1 gallon per minute (gpm). If landfill gas is vented (short-term methane present, vent layer present), percolation decreases to about 0.1 to 0.3 cm/yr. As the landfill ages and landfill gas production falls, roots grow deeper into the profile (modeled at 105 cm [42 inches]) and the landfill begins to discharge water at about 0.1 cm/yr. For the RFETS site, the objective is to design a cover with a modeled infiltration rate of less than or equal to 0.3 cm/yr.

A.4.3 Scenario 3: Conventional Cover

In evaluation of alternative covers, percolation performance is generally compared to a conventional cover design. However, even conventional covers vary in how cross sections are defined. To provide a simple basis for comparison between the proposed ET cover and the conventional design, a simple, high-performance standard cross section with a flawlessly installed flexible membrane liner (FML) having an intact permeability of 10^{-13} cm/s was modeled.

The Present Landfill conventional cover consists of a multilayered system as shown in Figure A-1. The erosion protection/soil-rooting medium layer has a thickness of 24 inches (60 cm) with the values described in Table A-3, except the saturated hydraulic conductivity is set at 1.0×10^{-5} cm/s . The FML would overlie a 2-foot (60-cm) clay layer with the values presented in Table A-3. As specified in an RFETS technical memorandum (EG&G, 1994), the waste material averages 11 feet (3.5 meters) thick.

The UNSAT-H model predicted runoff for the conventional cover design of 30 cm/yr, transpiration of 5 cm/yr, and a drainage rate of –0.07 cm/yr (upward). The mass balance error was –0.71 cm/yr (Table A-5; Attachment A1, Figure A1-83). Larger mass balance errors are typically associated with higher runoff. A drainage rate of –0.07 cm/yr is indistinguishable from the 0-cm recharge calculated for the 60-cm- (2-foot-) thick alternative cover results presented in Section 4.1.

A.5 Overall Results and Conclusions

The proposed Present Landfill ET cover has fine-grained soils and the capability to store infiltrating water until vegetation can transpire the water back to the atmosphere during the growing season. UNSAT-H treats any precipitation that cannot infiltrate into the surface material, based on the hydraulic conductivity of the surface material, as runoff that is lost to the system. The vegetation and rock will act in concert to control erosion by wind and water and will provide sufficient transpiration to limit percolation.

Denver Stapleton airport data were shown to be the best available and a reasonable data set to examine the interactions of climate with the soils and vegetation present at RFETS. The modeling results indicated that an ET cover is capable of achieving upward flux or no flux during periods of above-average precipitation. A comparison of percolation through the ET cover and

Table A-5. Modeling Results for Present Landfill Conventional Cover

Run	Notes	Year	Precipitation (cm)	Infiltration (cm)	Runoff (cm)	Evaporation (cm)	Transpiration (cm)	Drainage (cm)	Mass Balance Error (cm)
19		1965	55.55	18.72	36.83	13.94	6.58	–0.07	0.11
		1966	27.46	13.05	14.41	10.35	3.97	–0.07	–1.05
		1967	59.21	19.51	39.70	13.24	5.65	–0.07	0.14
		1968	30.81	14.15	16.66	10.90	3.44	–0.07	0.11
		1969	54.66	15.97	38.69	12.20	4.92	–0.07	–2.87
Average of last 5 years		NA		16.28	29.26	12.13	4.91	–0.07	–0.71

cm = Centimeter NA = Not applicable

MODEL FOR CONCEPTUAL DESIGN OF AN EVAPOTRANSPIRATION COVER FOR THE PRESENT LANDFILL 4-15-02

the conventional cover indicated that the percolation rates in the ET cover were approximately the same as those in the conventional cover.

This investigation has demonstrated the following:

- The proposed 2-foot- (60-cm-) thick ET cover at the Present Landfill is equivalent to the conventional cover.
- Percolation for the ET cover is essentially zero.
- Local soil is available and suitable for the proposed ET cover system.
- Native vegetation and proposed vegetation will be suitable for the proposed ET cover.
- Thicker covers, up to approximately 2 feet (60 cm), significantly improve performance. Beyond 2 feet (60 cm), little added performance benefit is seen (Table A-4).
- Modeling of the effects of rooting depth also shows that a venting layer is needed at the Present Landfill to provide oxygen to plant root systems.

These results are consistent with nearby research experience at RMA and support the conclusion that the potential for water percolation at the site is low.

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Attachment A1

Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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Attachment A1. Present Landfill Modeling Results

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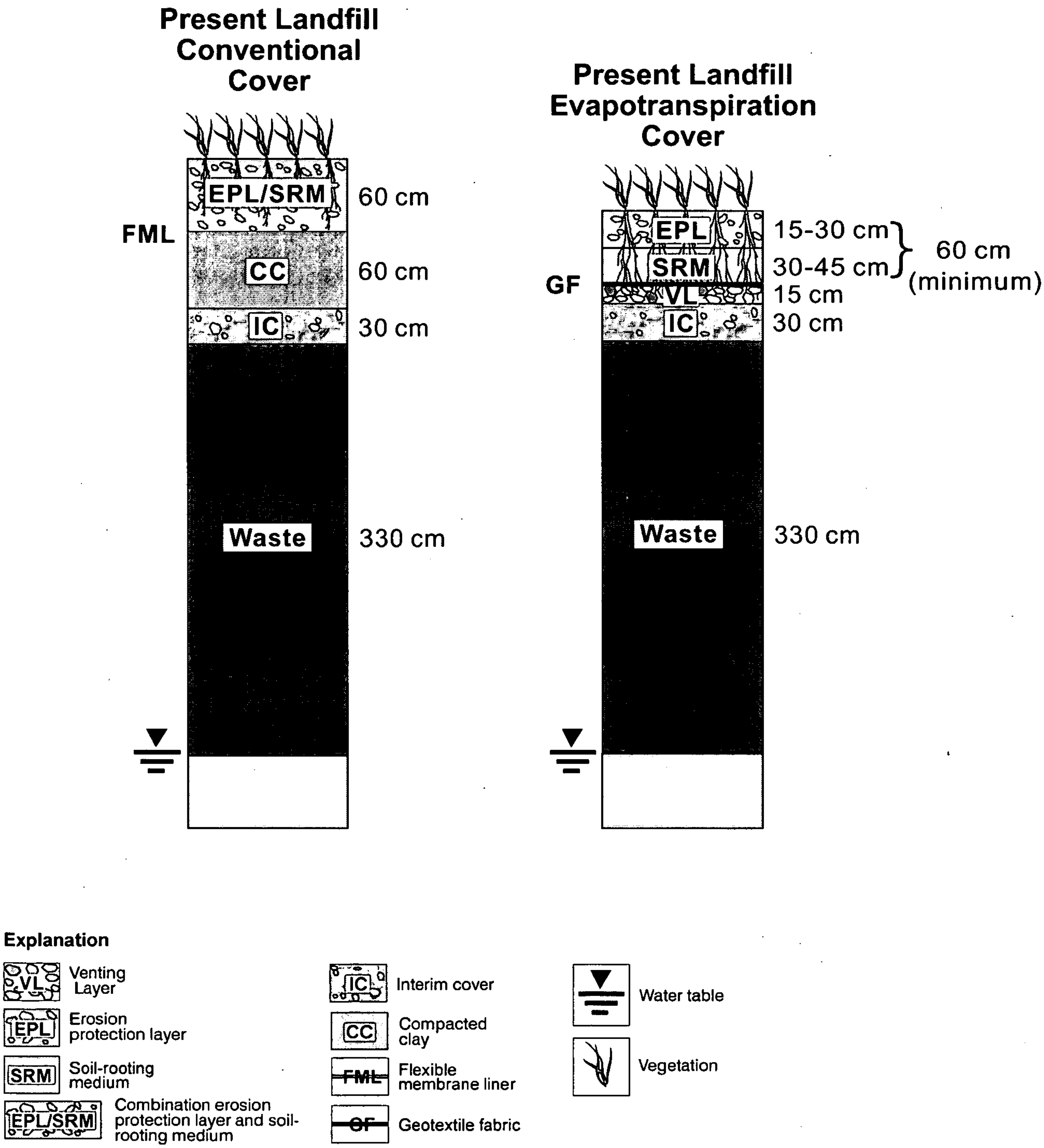

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ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Modeled Cover Cross-Sections

Figure A1-1

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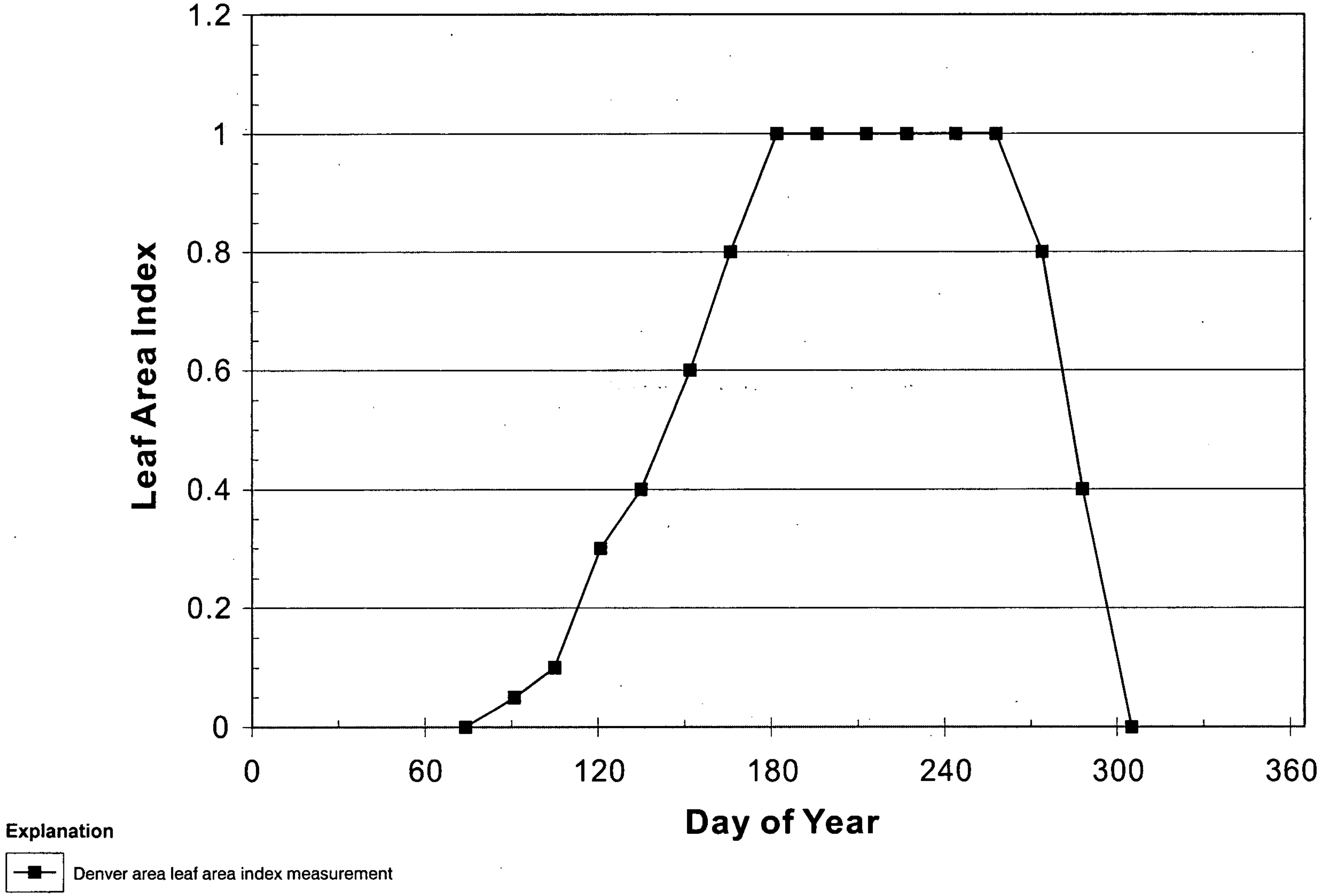

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Leaf Area Index

Figure A1-2

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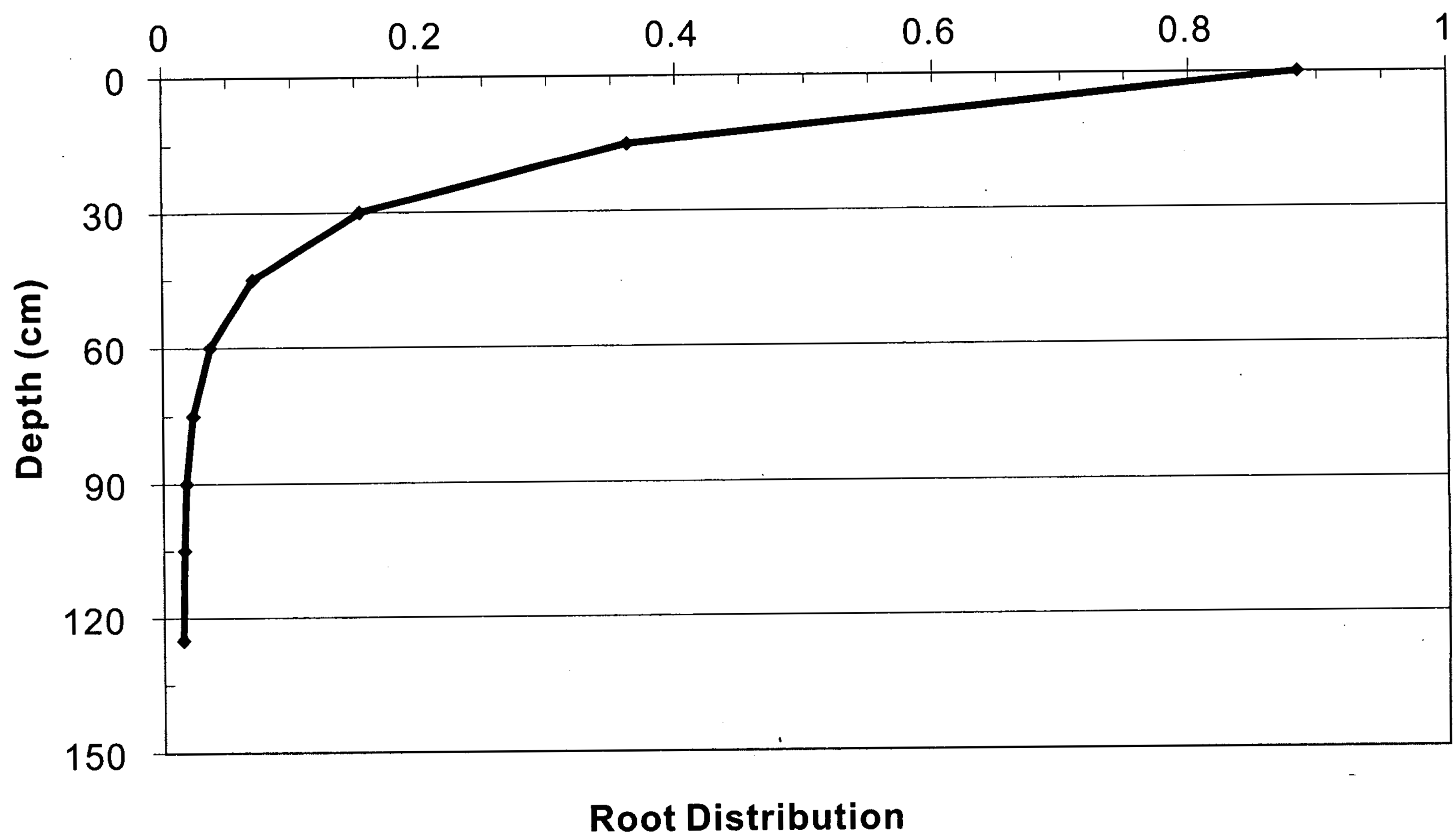

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Root Density Function

Figure A1-3

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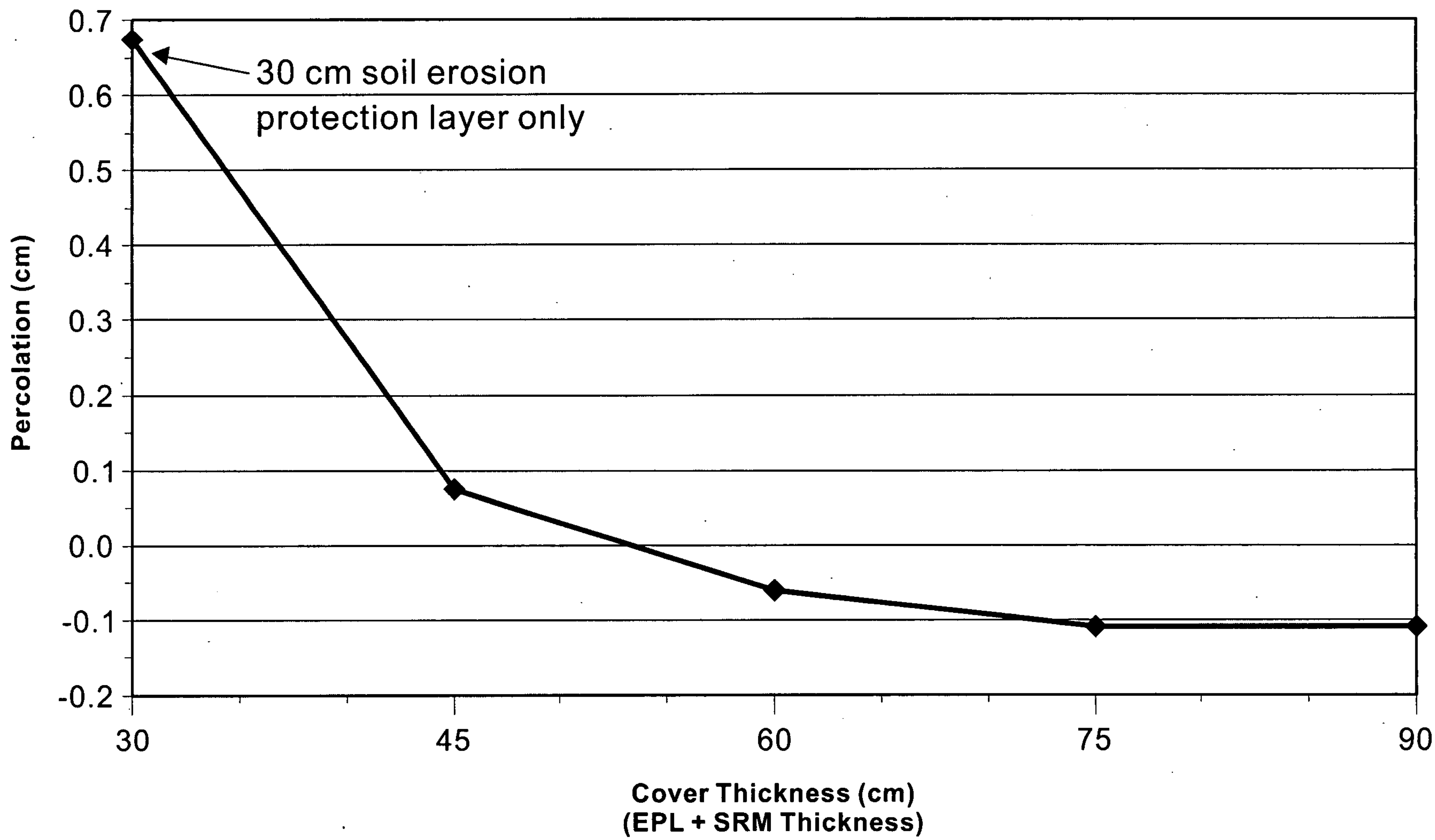

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Present Landfill

Percolation vs Cover Thickness

Figure A1-4

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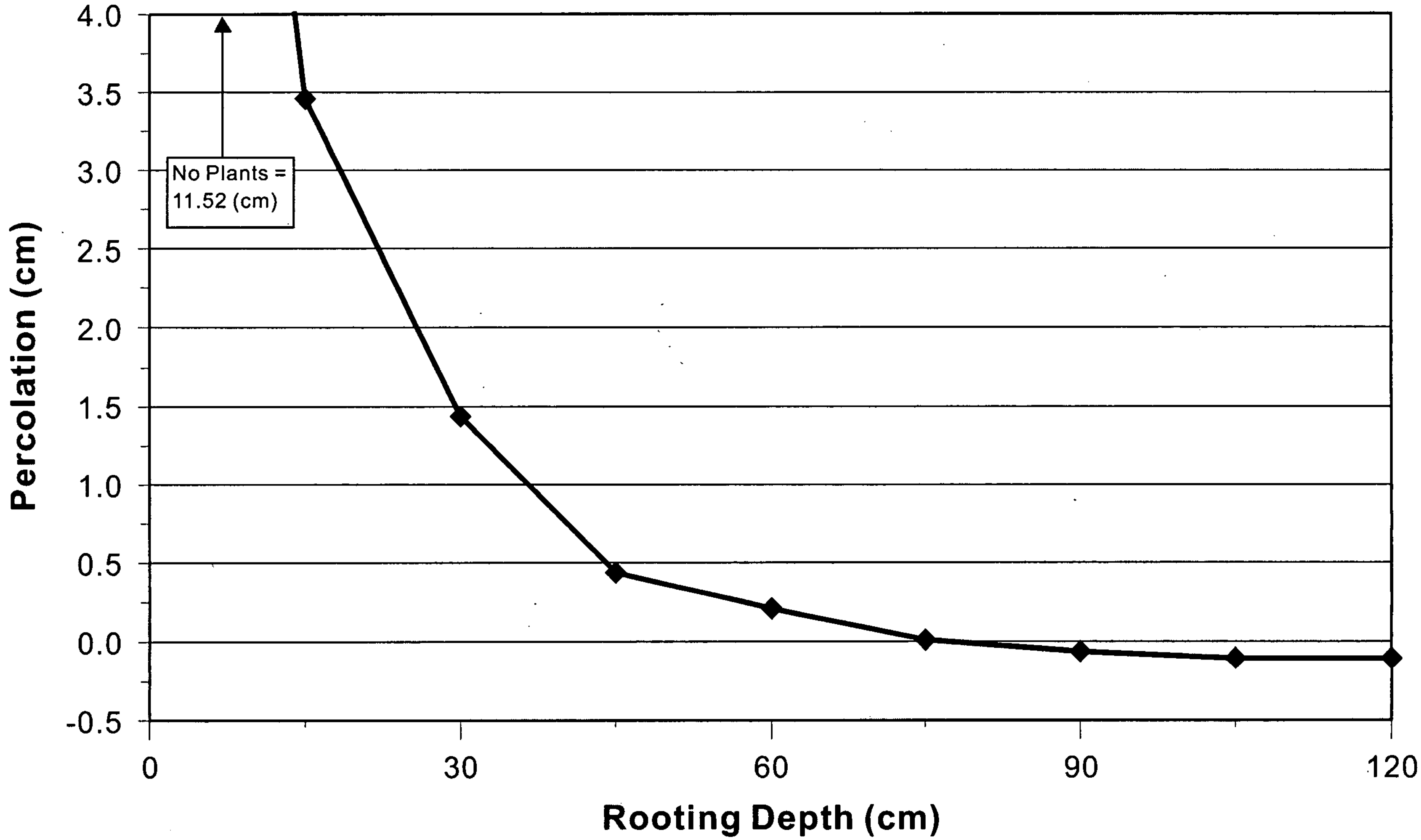

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Present Landfill
Percolation vs Rooting Depth

Figure A1-5

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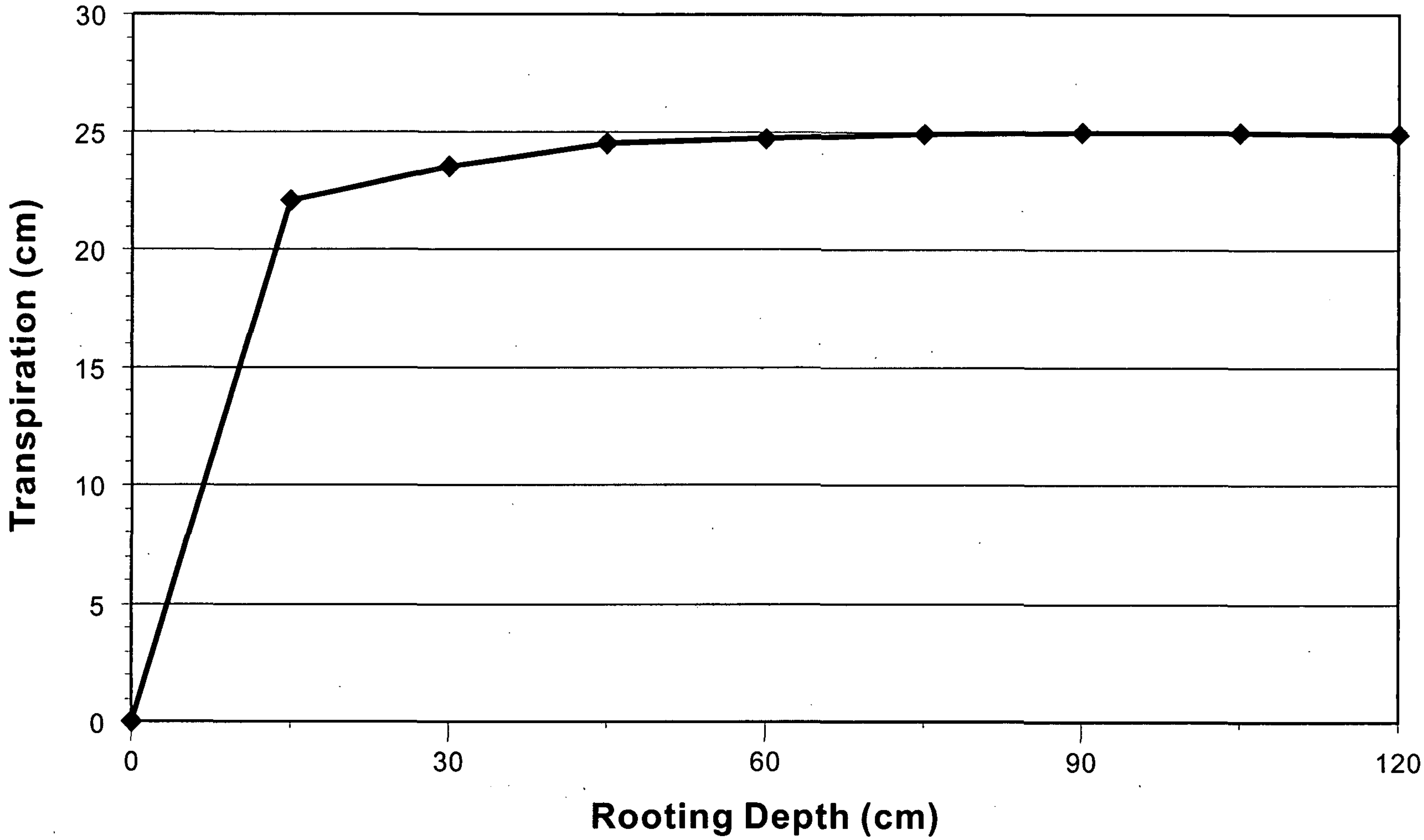

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Present Landfill

Transpiration vs Rooting Depth

Figure A1-6

57

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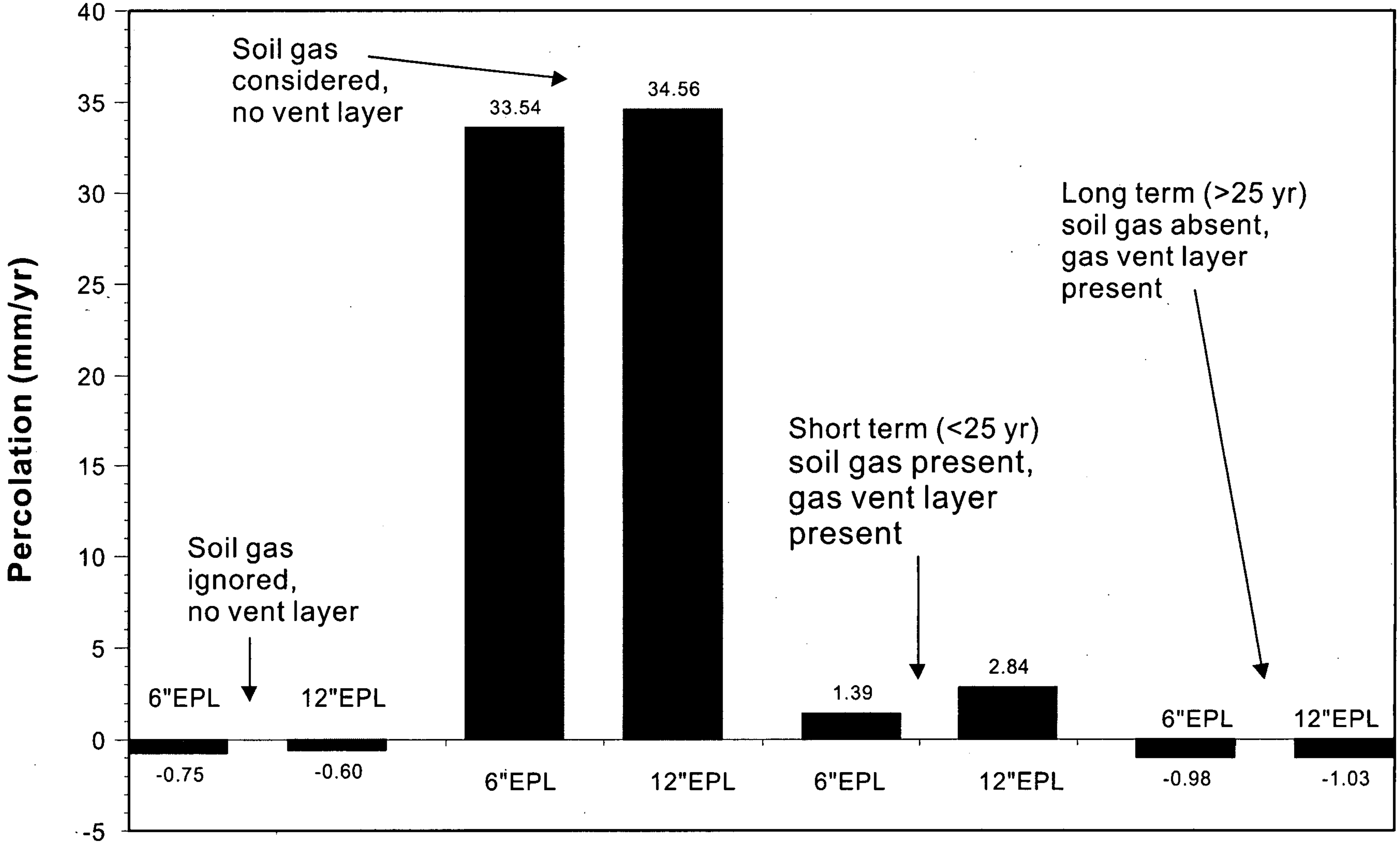

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Percolation vs Rooting Depth and Erosion Protection Layer Thickness

Figure A1-7

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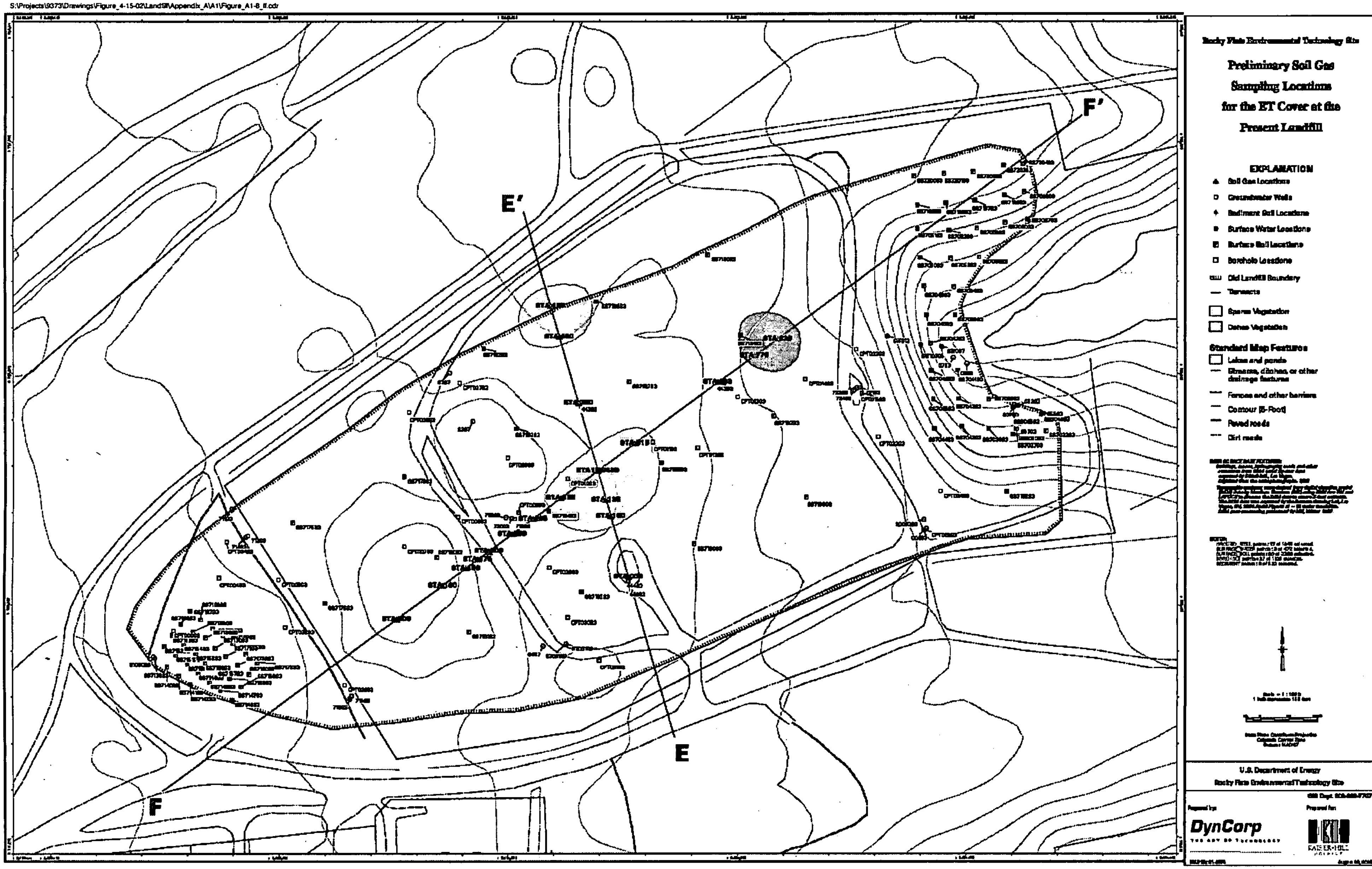

Figure A1-8

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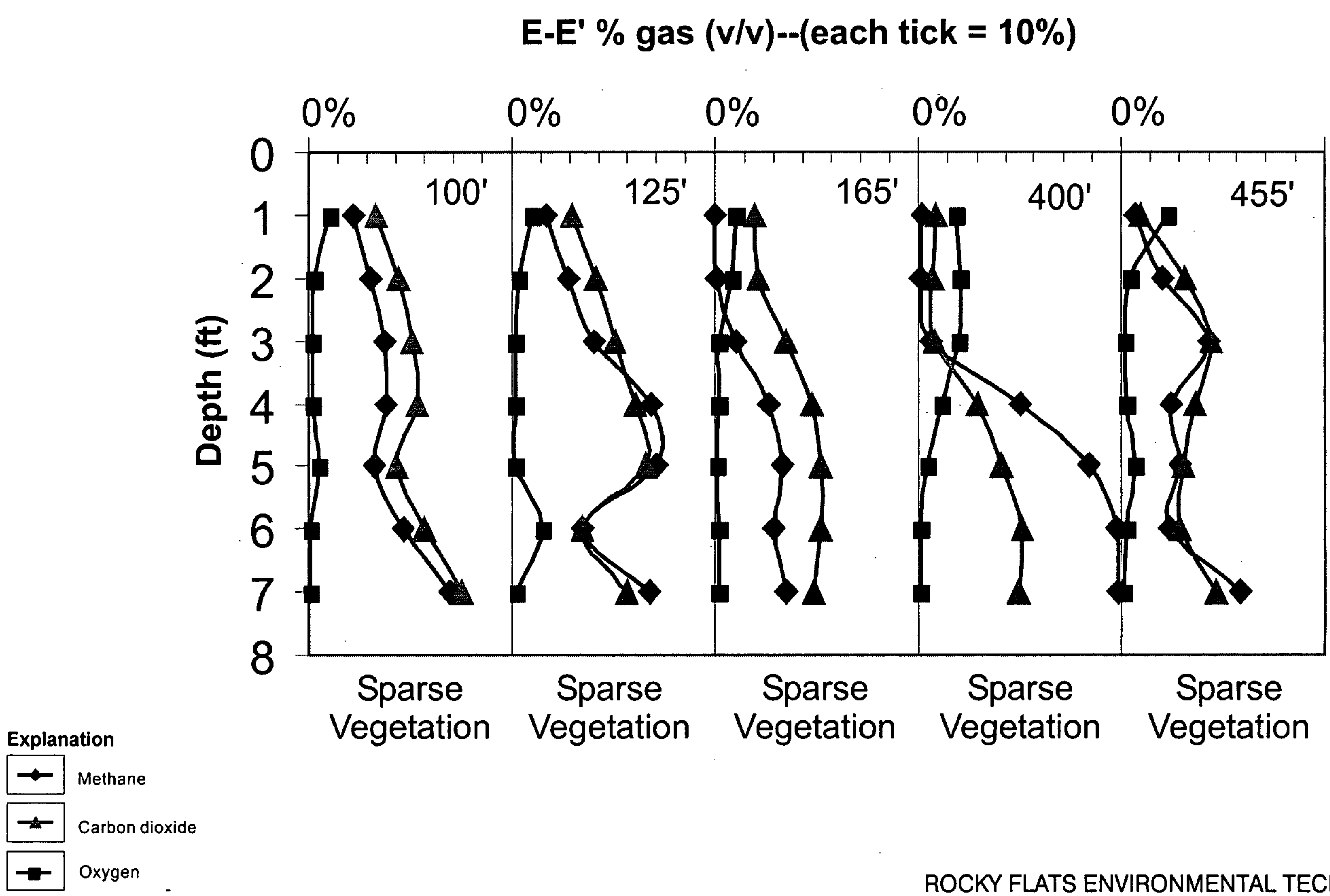

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Soil Gas Profiles

Figure A1-9

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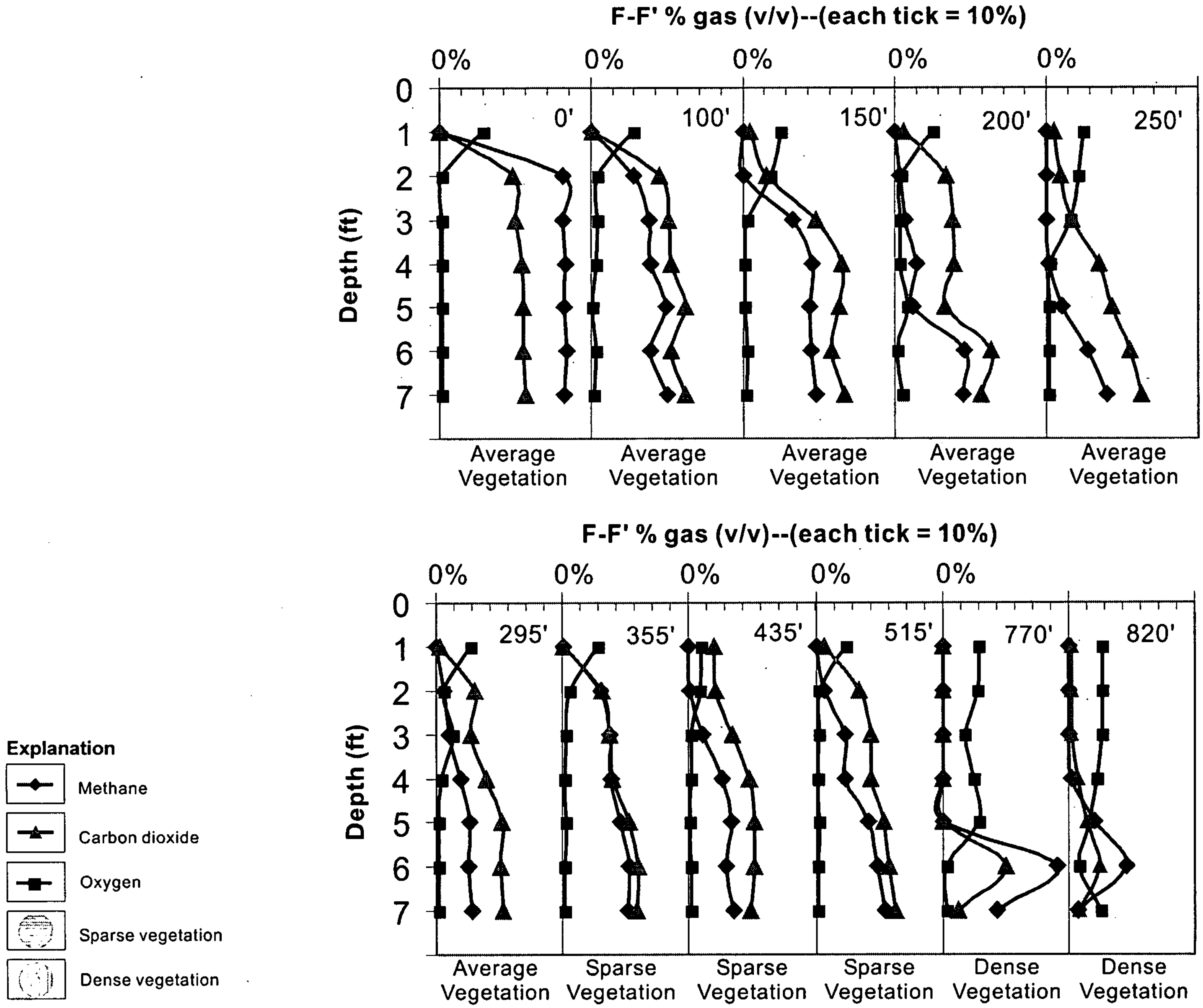

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Soil Gas Profiles

Figure A1-10

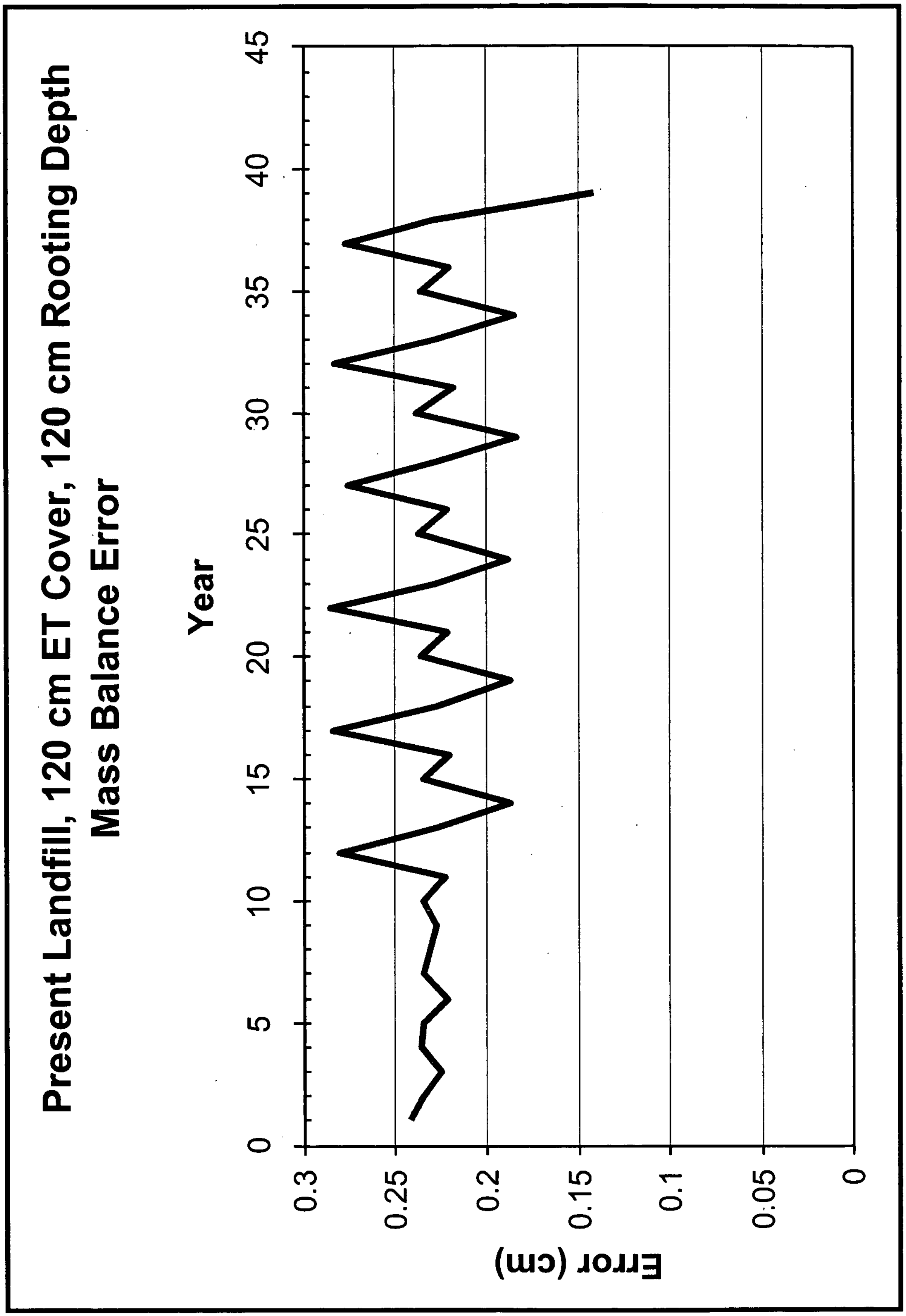
Present Landfill, 120 cm ET Cover, 120 cm Rooting Depth
Mass Balance Error
Year
Error (cm)
0
5
10
15
20
25
30
35
40
45
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-11

2c

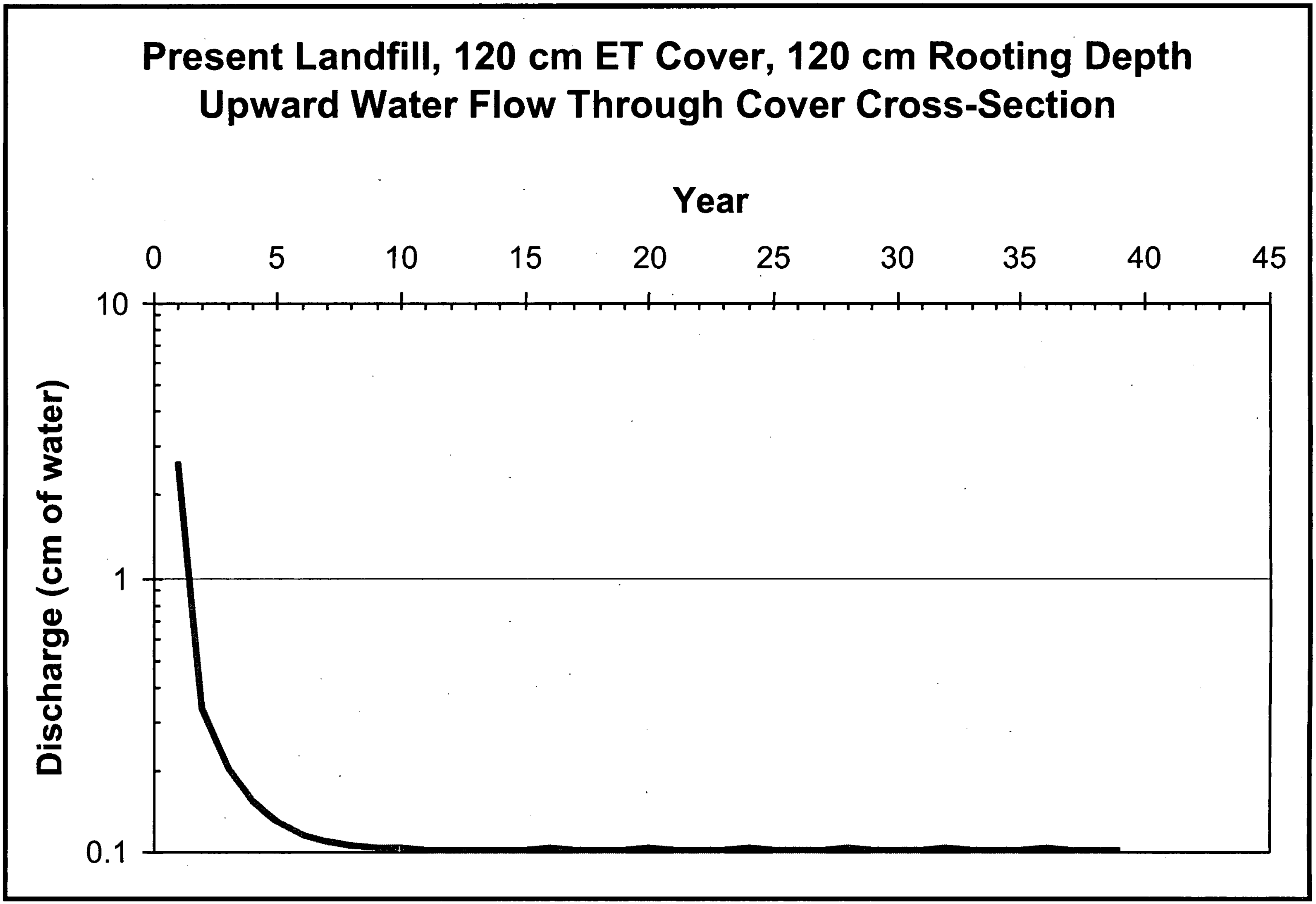

Figure A1-12

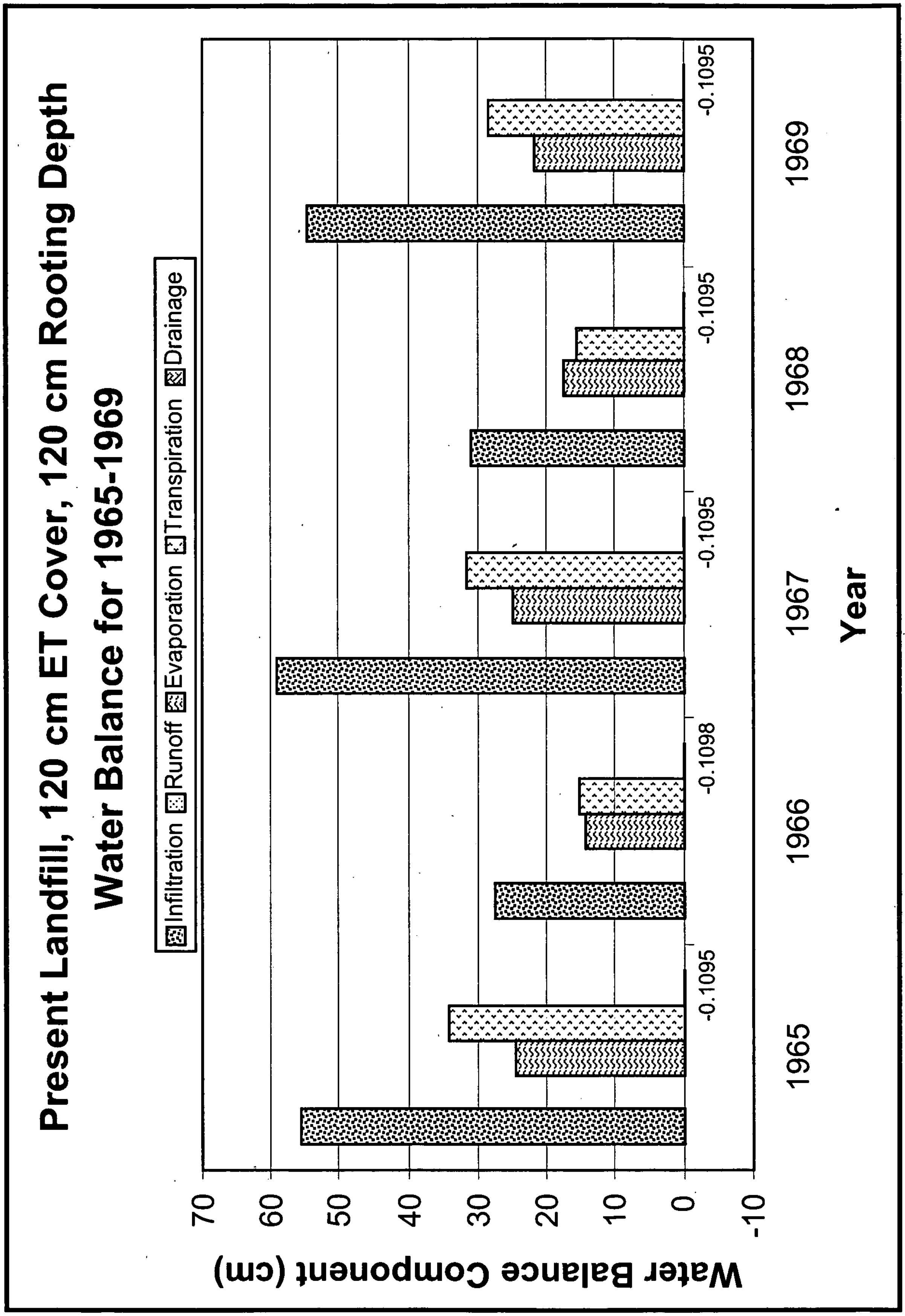

Figure A1-13

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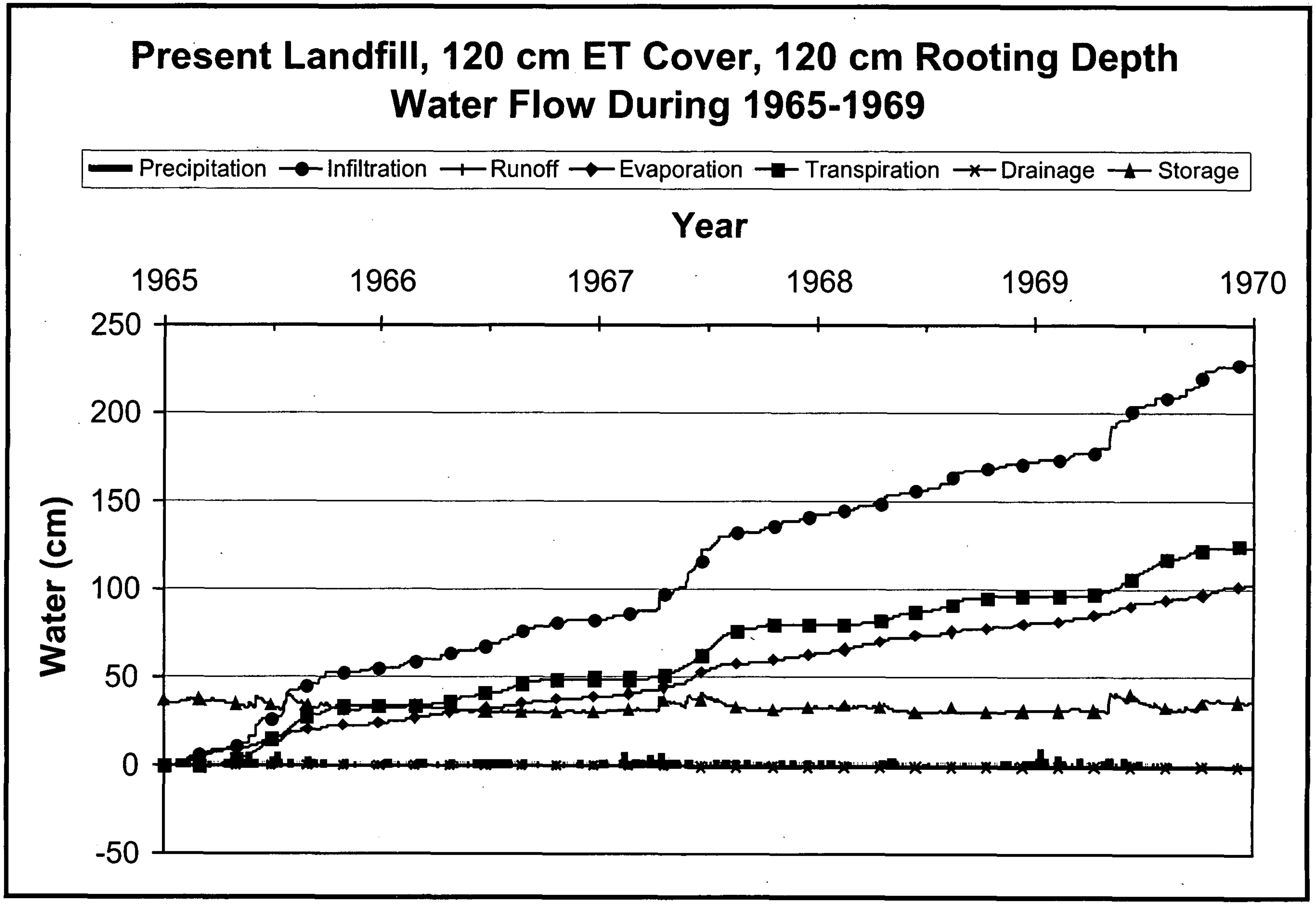


Present Landfill, 120 cm ET Cover, 120 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
Water (cm)
250
200
150
100
50
0
-50

Figure A1-14

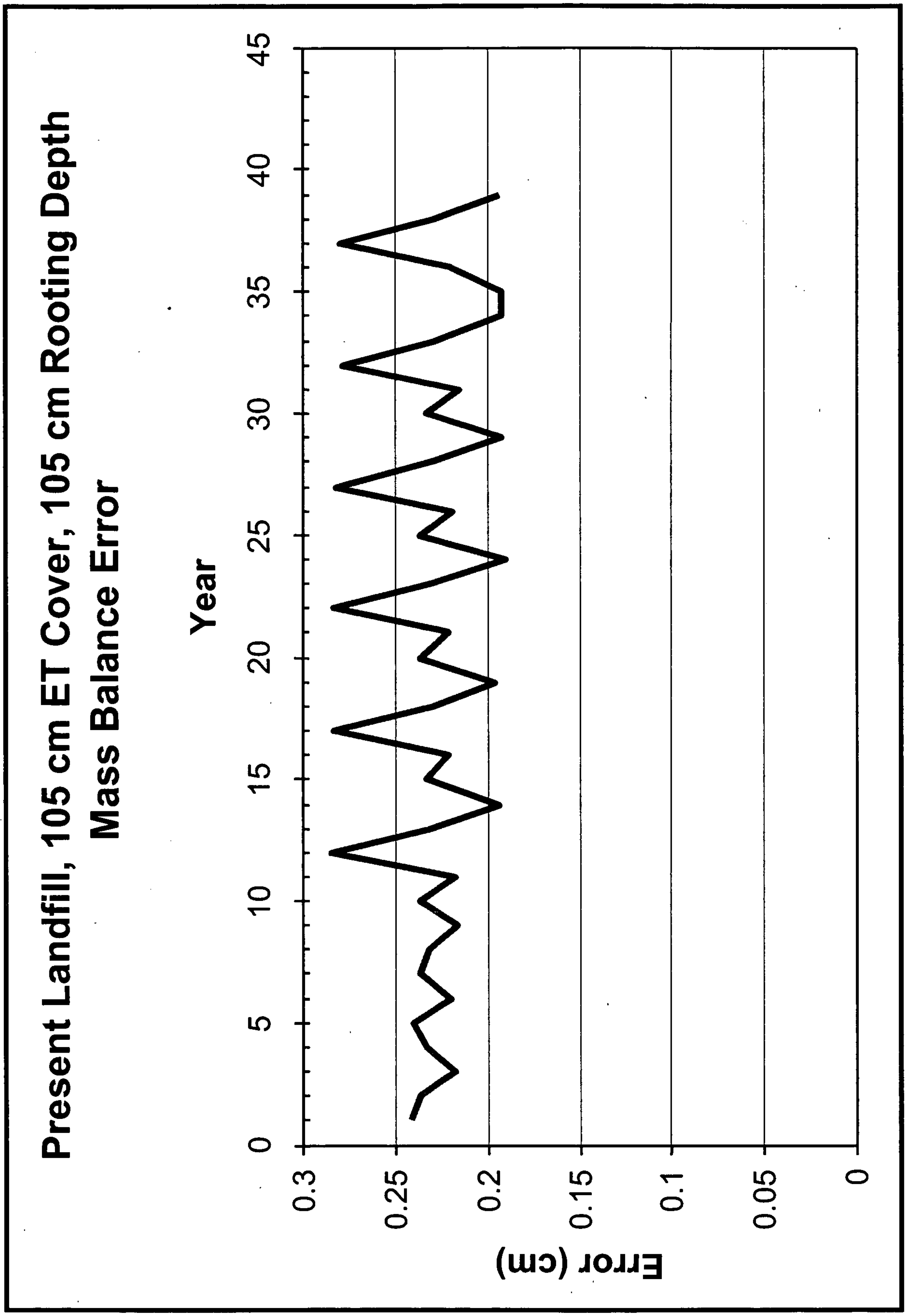
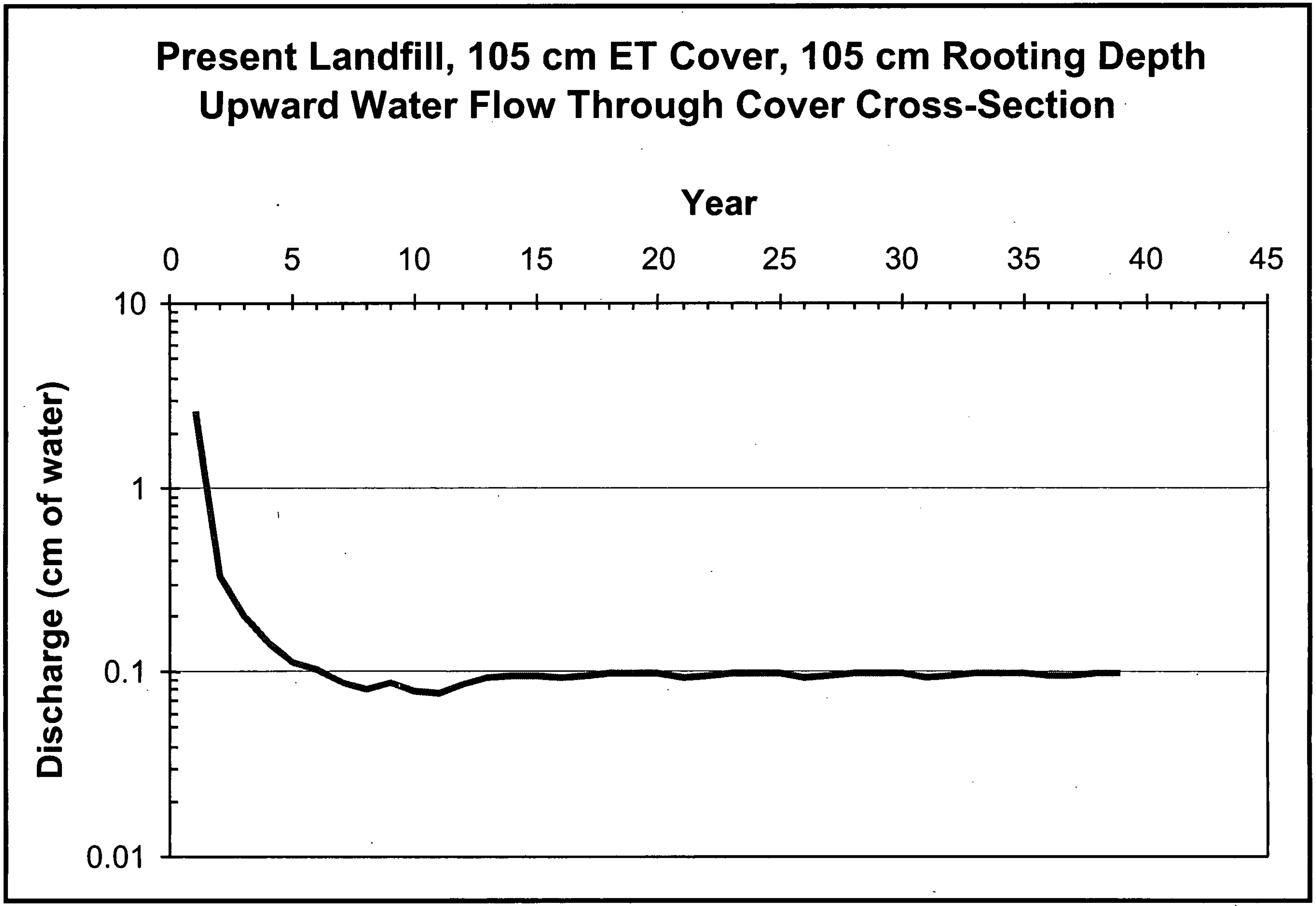

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
Mass Balance Error
Year
Error (cm)
0
5
10
15
20
25
30
35
40
45
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-15



Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
Upward Water Flow Through Cover Cross-Section
Year
0
5
10
15
20
25
30
35
40
45
Discharge (cm of water)
10
1
0.1
0.01

Figure A1-16

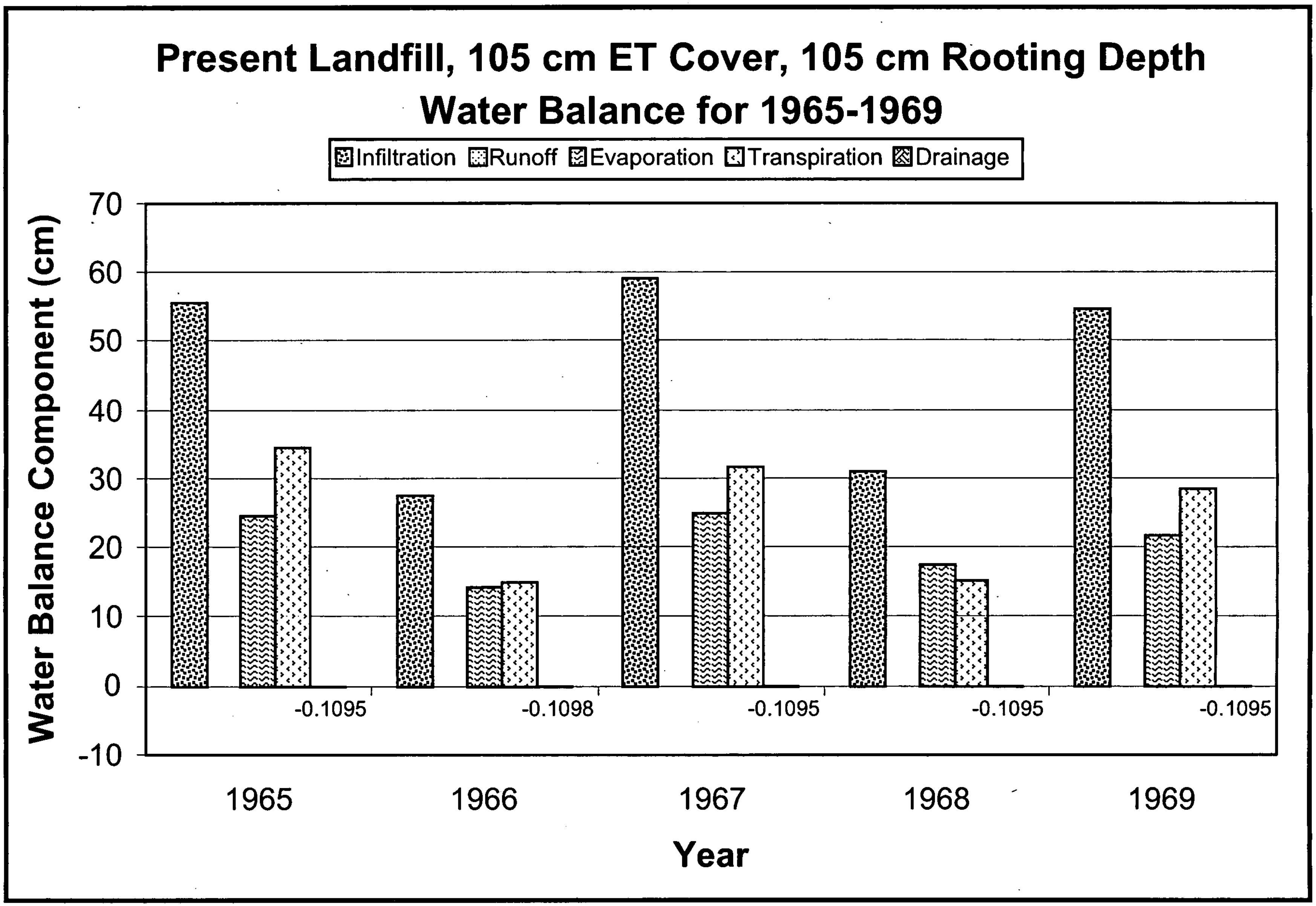

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
-10
-0.1095
-0.1098
-0.1095
-0.1095
-0.1095
1965
1966
1967
1968
1969
Year

Figure A1-17

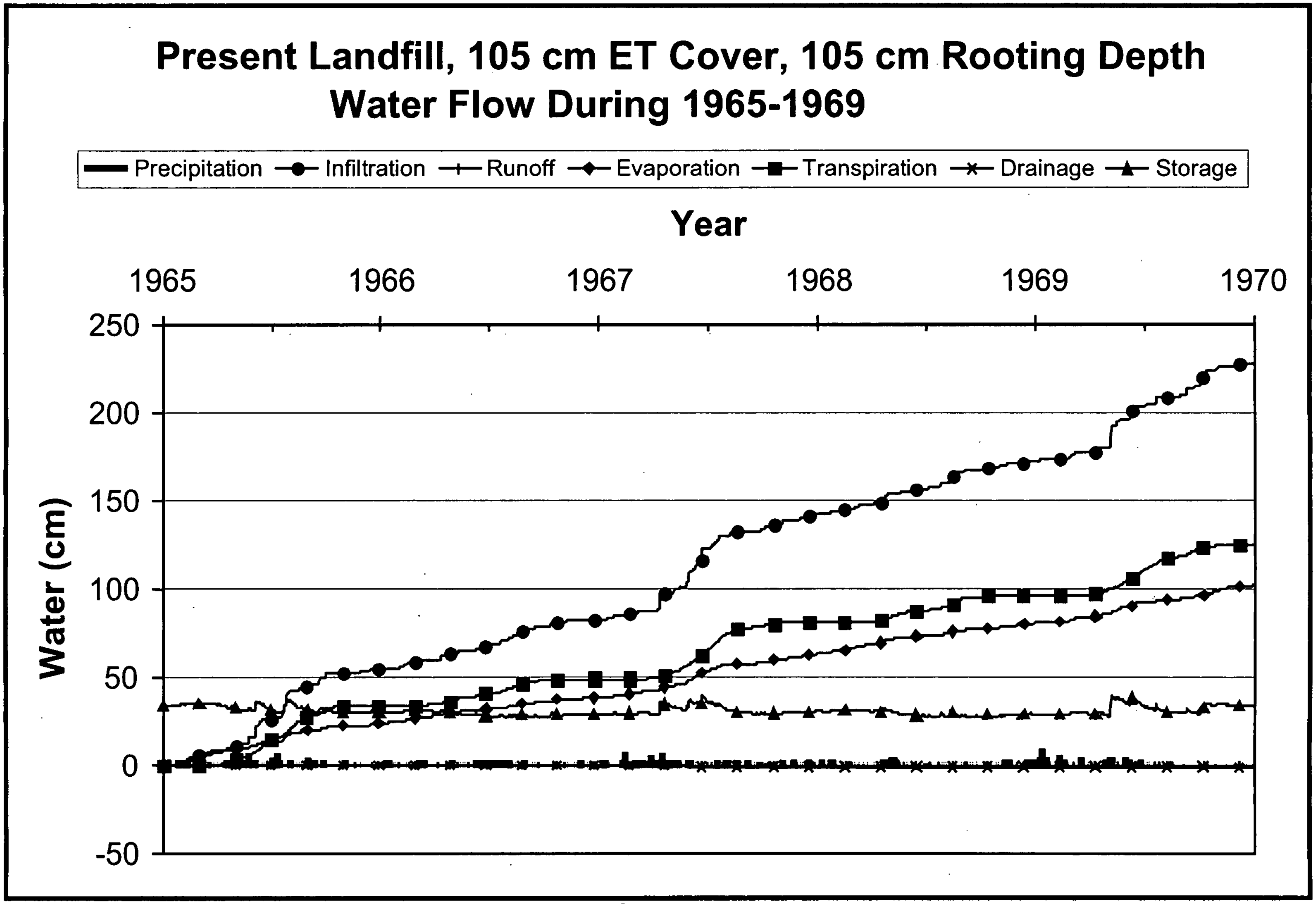

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
250
200
150
100
50
0
-50
Water (cm)

Figure A1-18

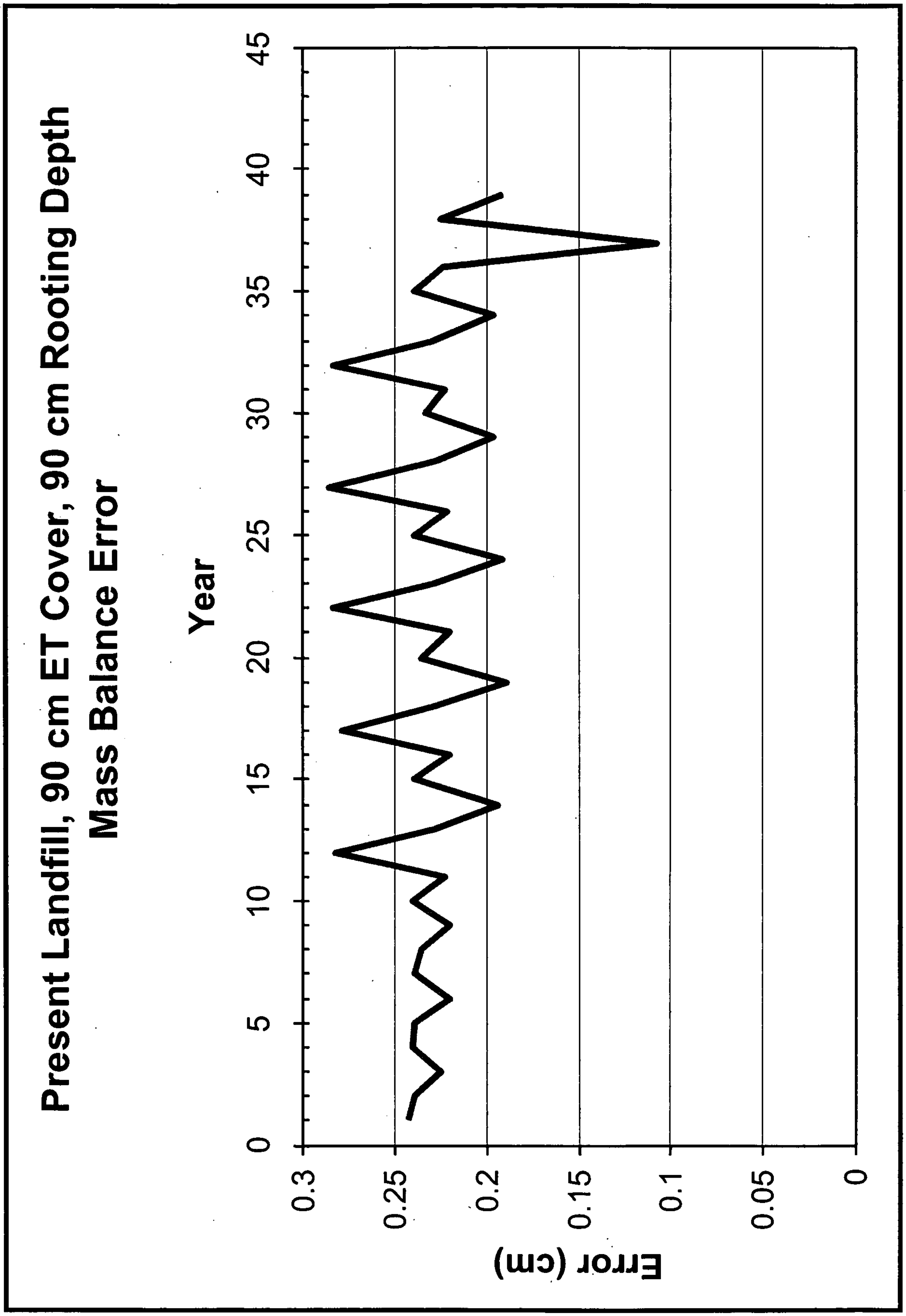

Present Landfill, 90 cm ET Cover, 90 cm Rooting Depth
Mass Balance Error
Year
Error (cm)
0
5
10
15
20
25
30
35
40
45
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-19

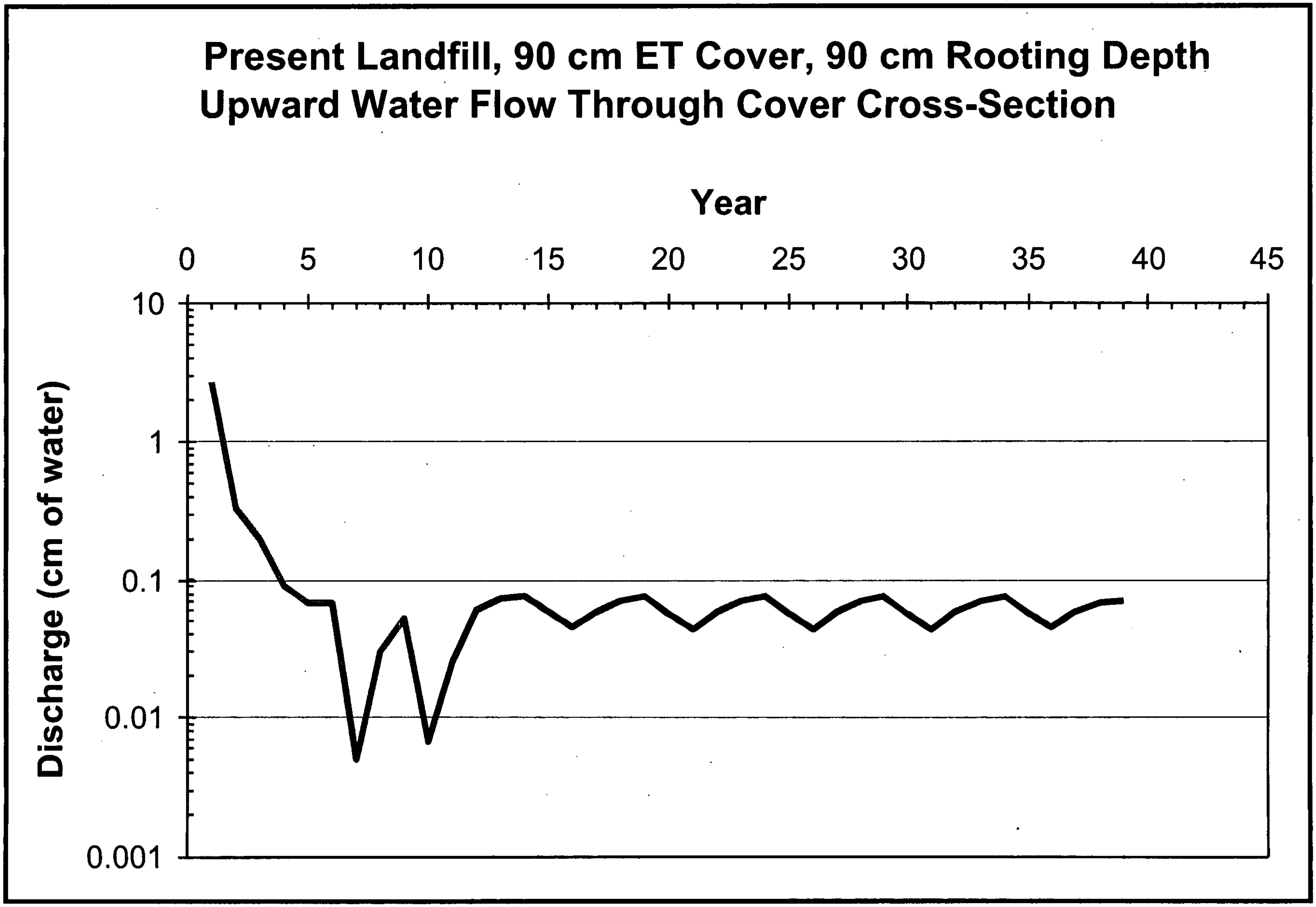


Figure A1-20

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65

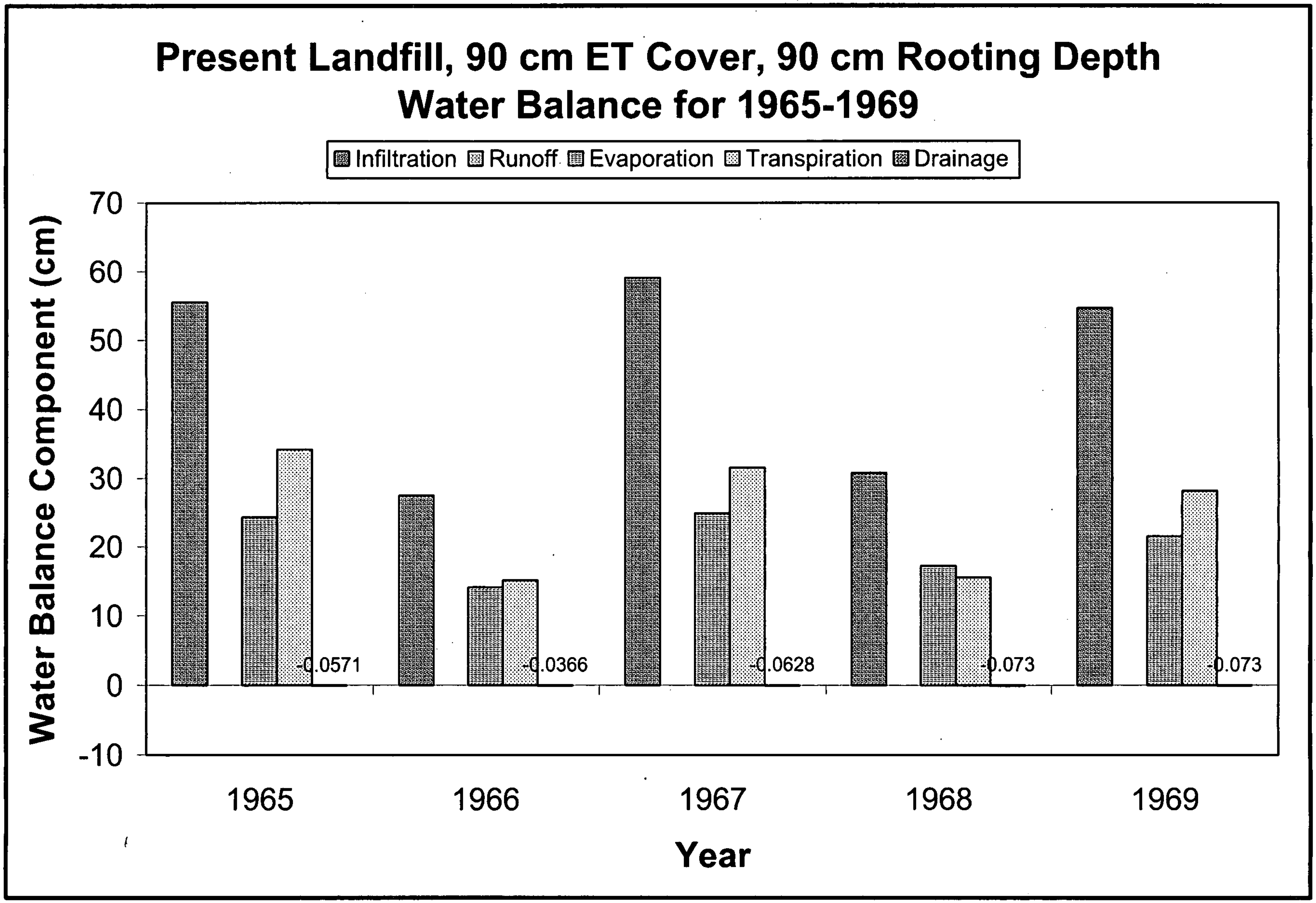
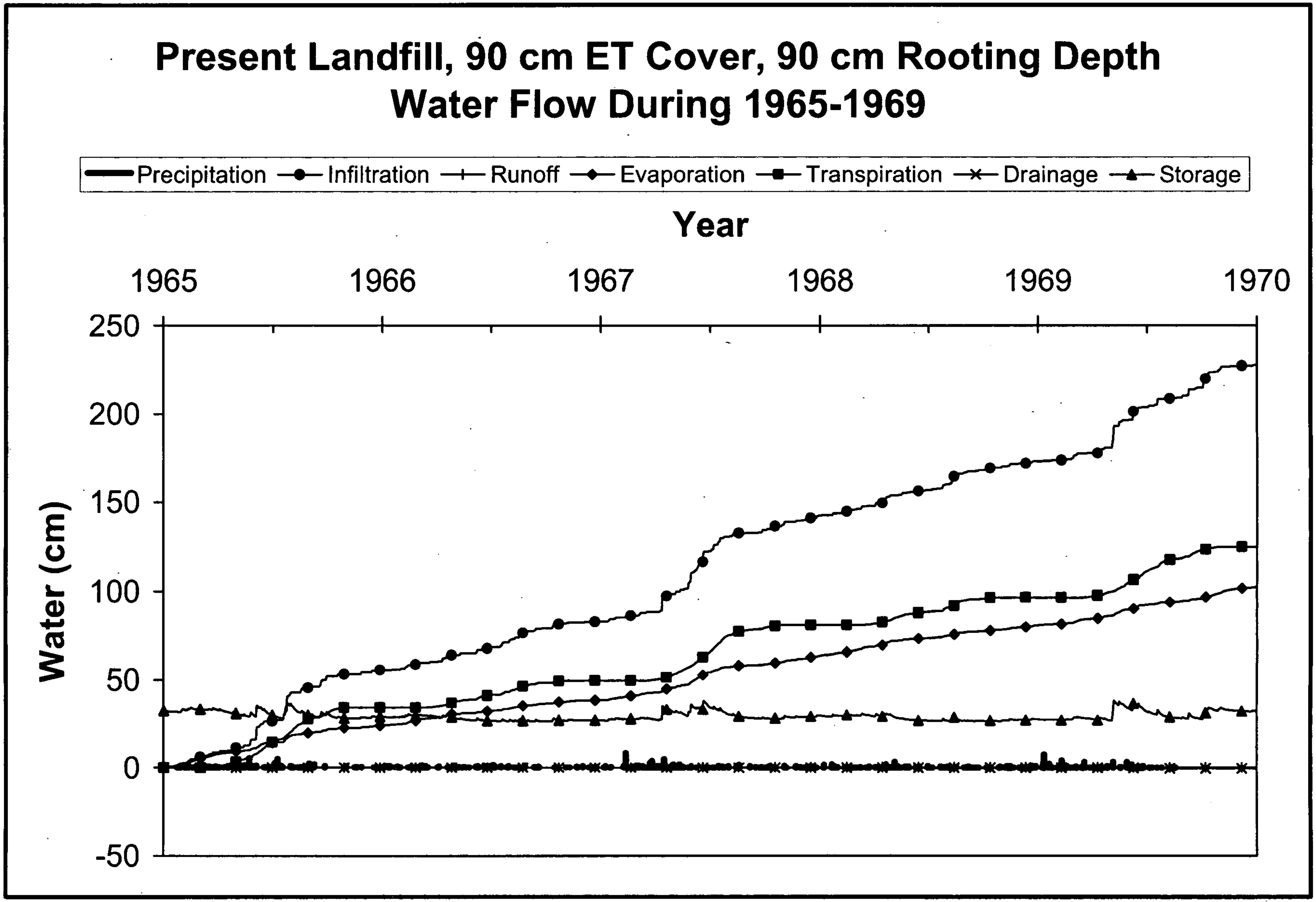


Figure A1-21



Present Landfill, 90 cm ET Cover, 90 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
Water (cm)
250
200
150
100
50
0
-50

Figure A1-22

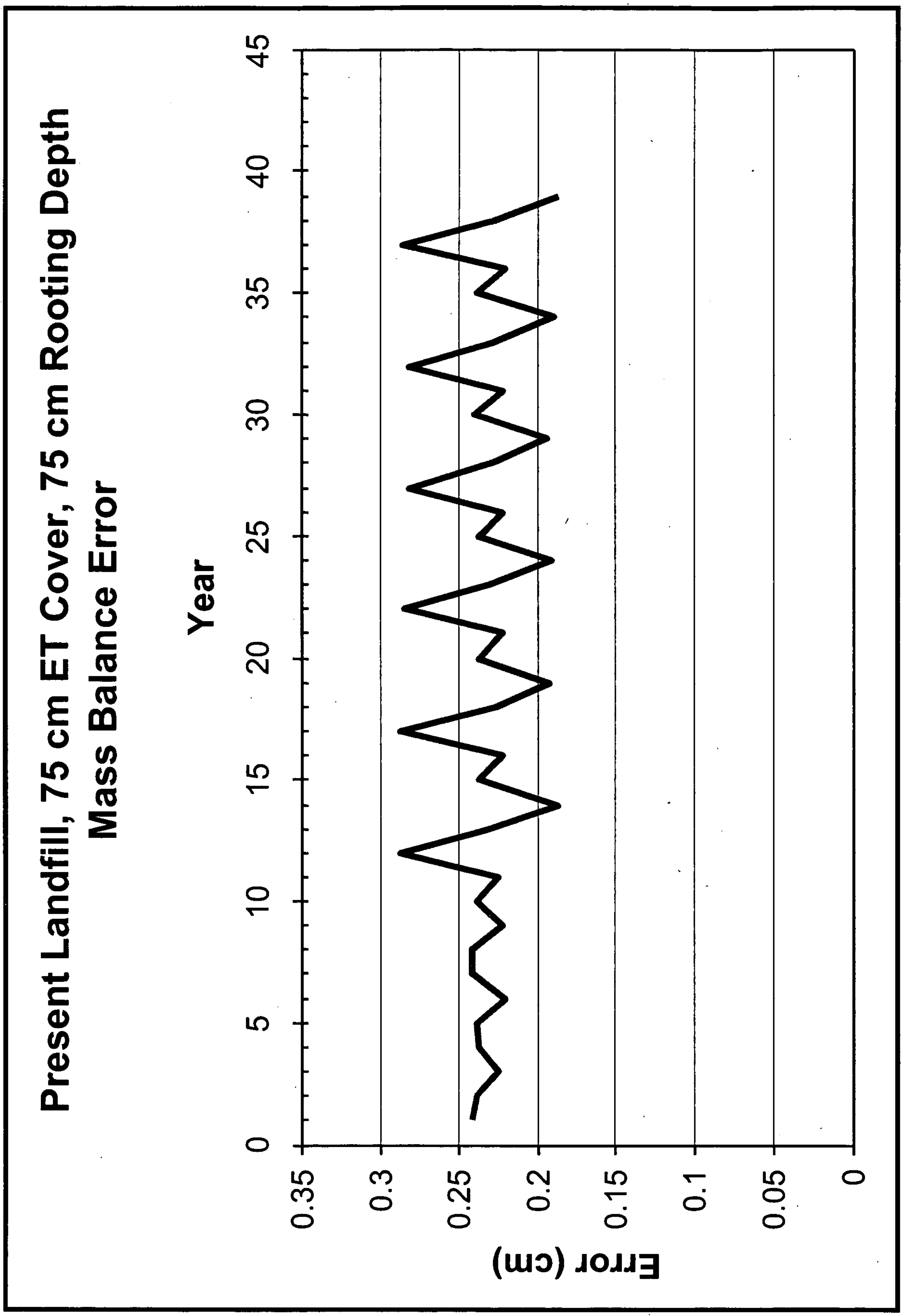


Figure A1-23

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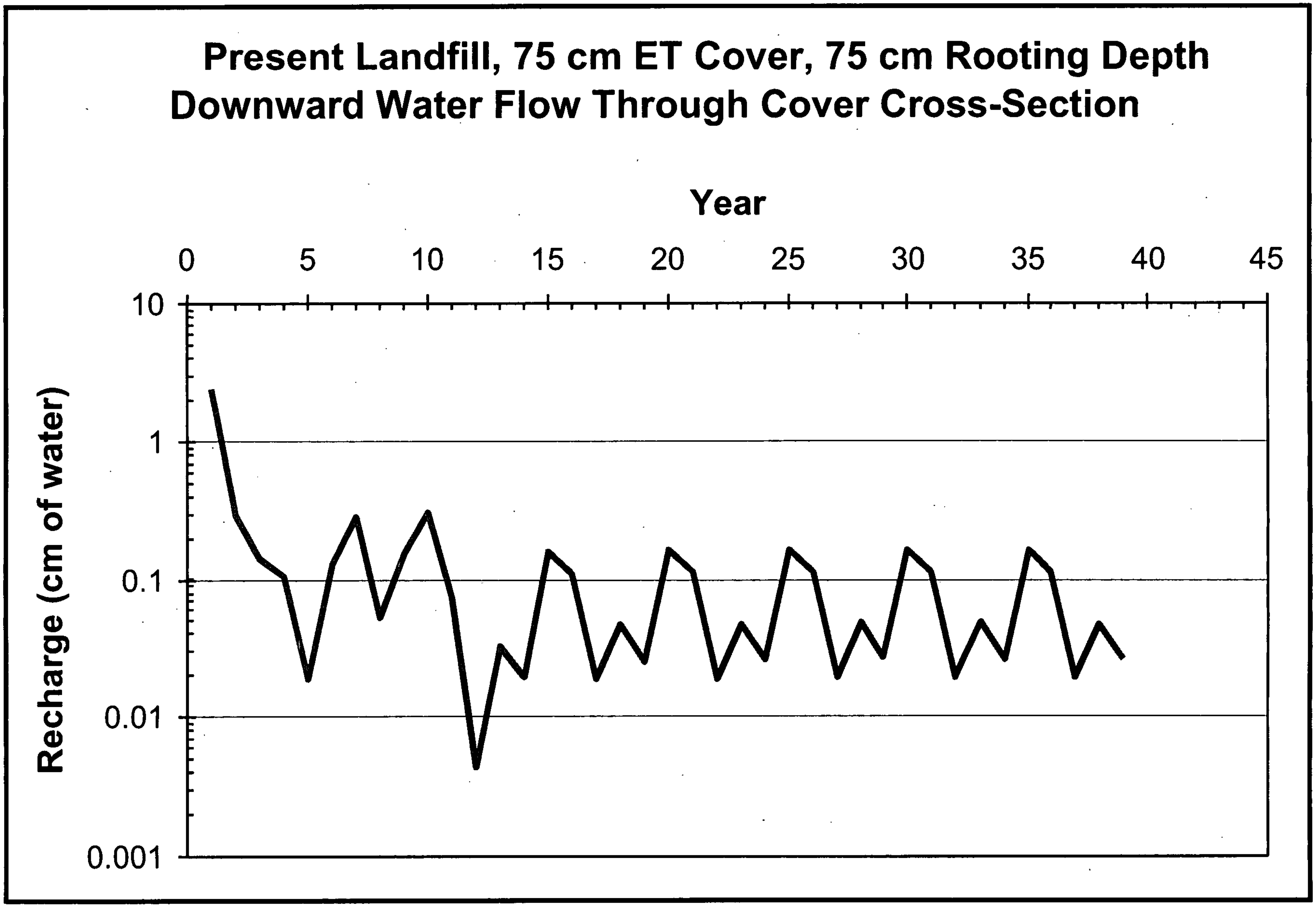
Present Landfill, 75 cm ET Cover, 75 cm Rooting Depth
Downward Water Flow Through Cover Cross-Section
Year
0
5
10
15
20
25
30
35
40
45
10
1
0.1
0.01
0.001
Recharge (cm of water)

Figure A1-24

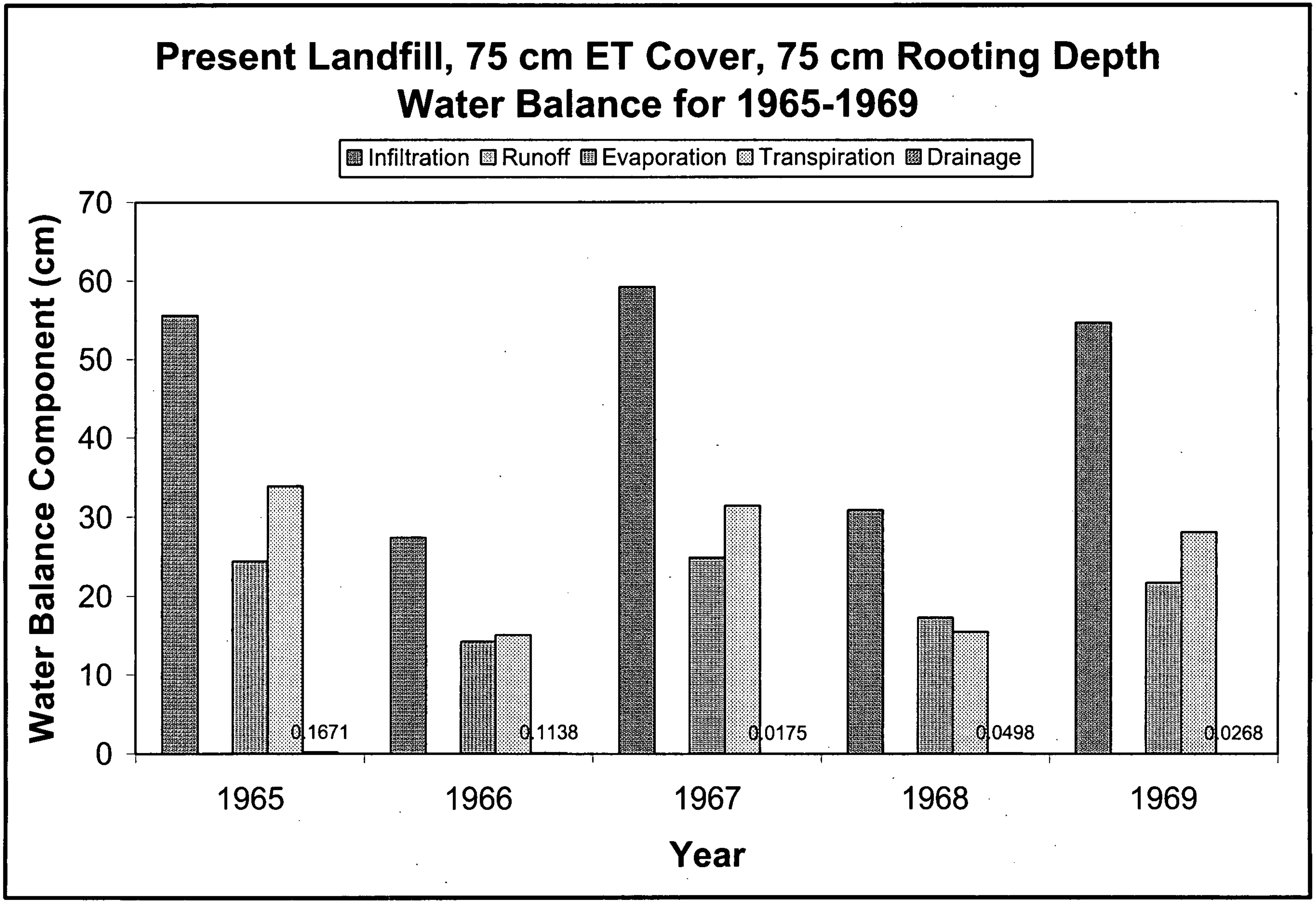
Present Landfill, 75 cm ET Cover, 75 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
0.1671
0.1138
0.0175
0.0498
0.0268
1965
1966
1967
1968
1969
Year

Figure A1-25

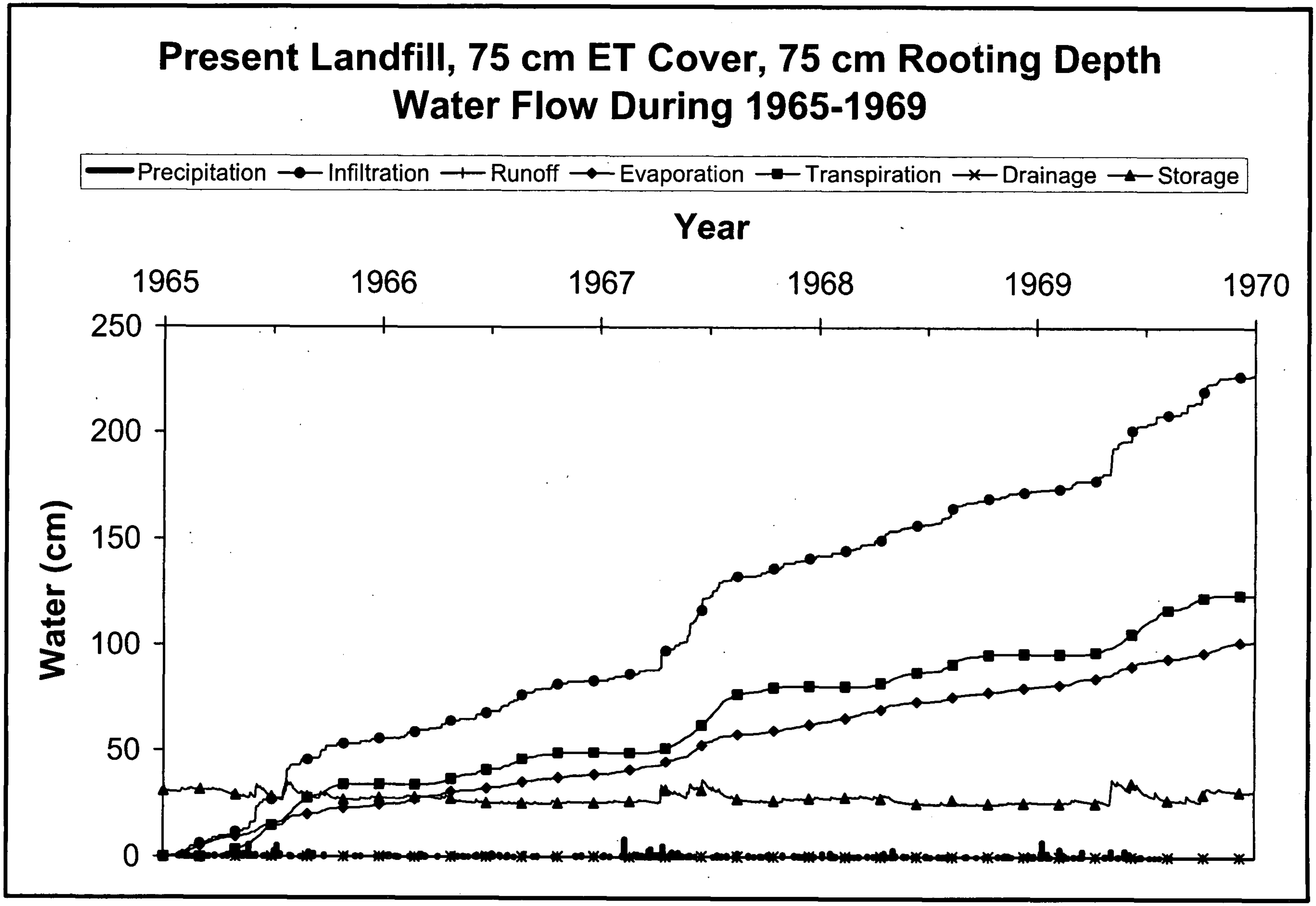
Present Landfill, 75 cm ET Cover, 75 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
250
200
150
100
50
0
Water (cm)

Figure A1-26

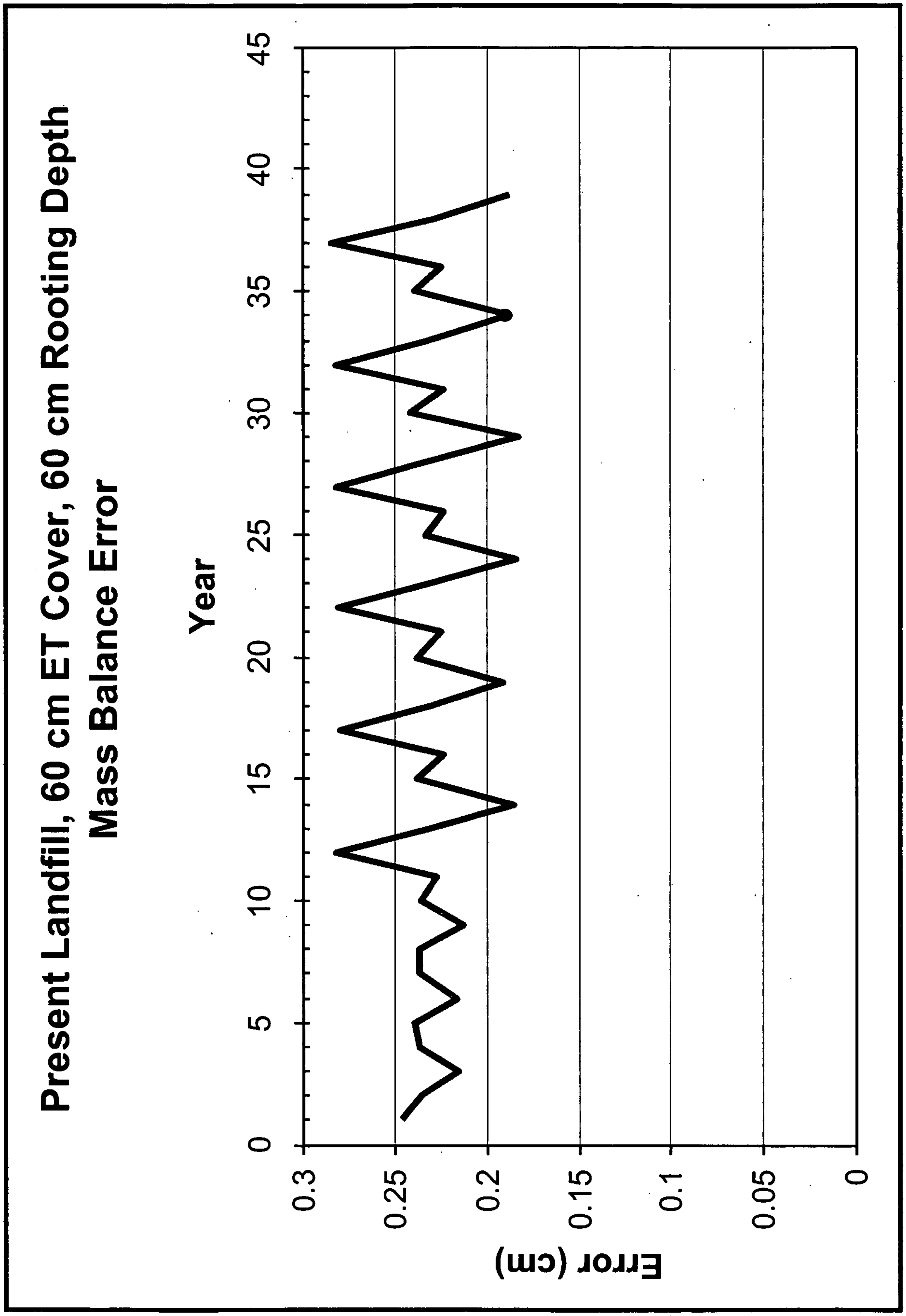
Present Landfill, 60 cm ET Cover, 60 cm Rooting Depth
Mass Balance Error
Year
Error (cm)
0
5
10
15
20
25
30
35
40
45
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-27

Present Landfill, 60 cm ET Cover, 60 cm Rooting Depth
Downward Water Flow Through Cover Cross-Section

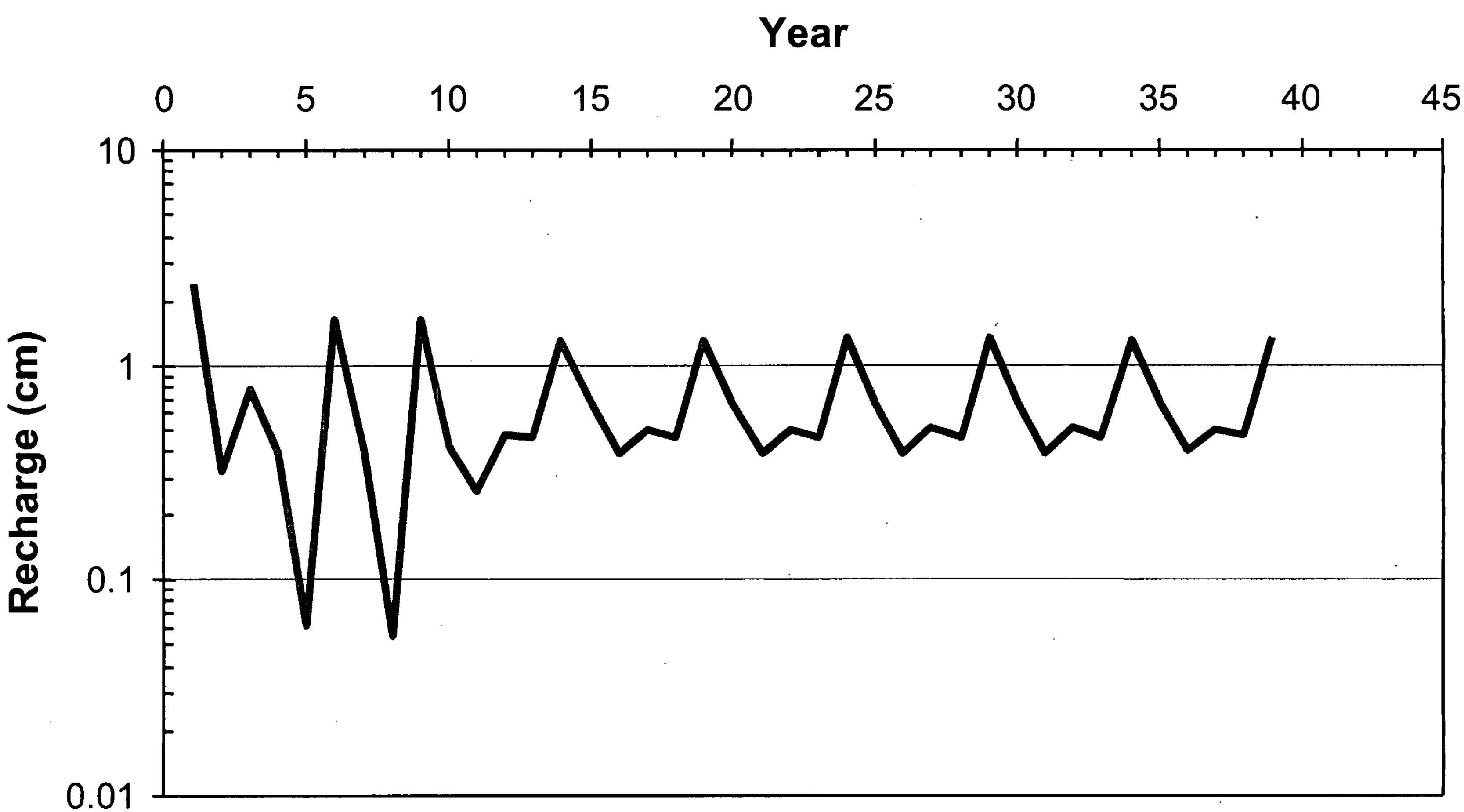

Figure A1-28

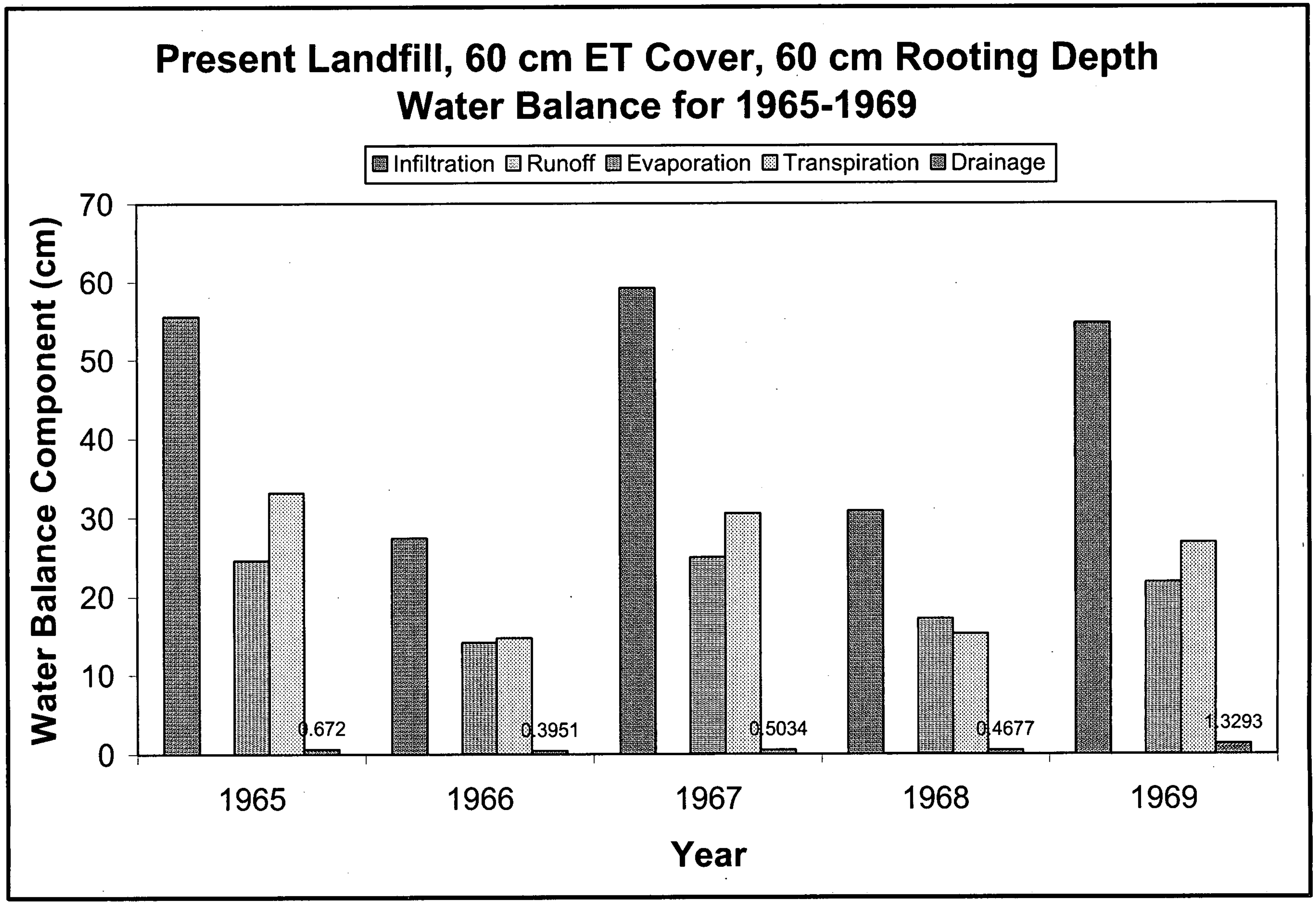
Present Landfill, 60 cm ET Cover, 60 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
0
10
20
30
40
50
60
70
0.672
0.3951
0.5034
0.4677
1.3293
1965
1966
1967
1968
1969
Year

Figure A1-29

Present Landfill, 60 cm ET Cover, 60 cm Rooting Depth
Water Flow During Last 5 Years

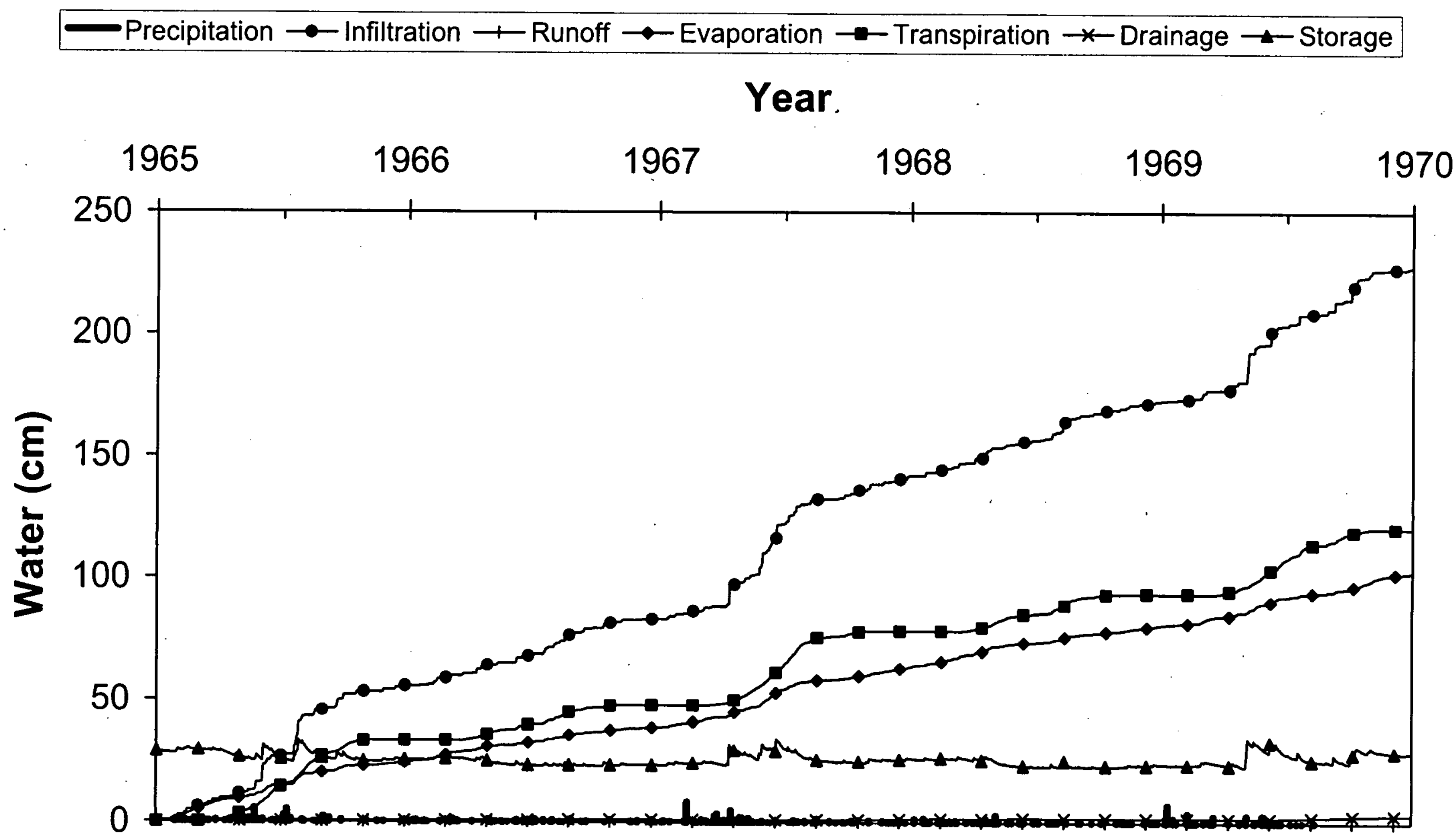

Figure A1-30

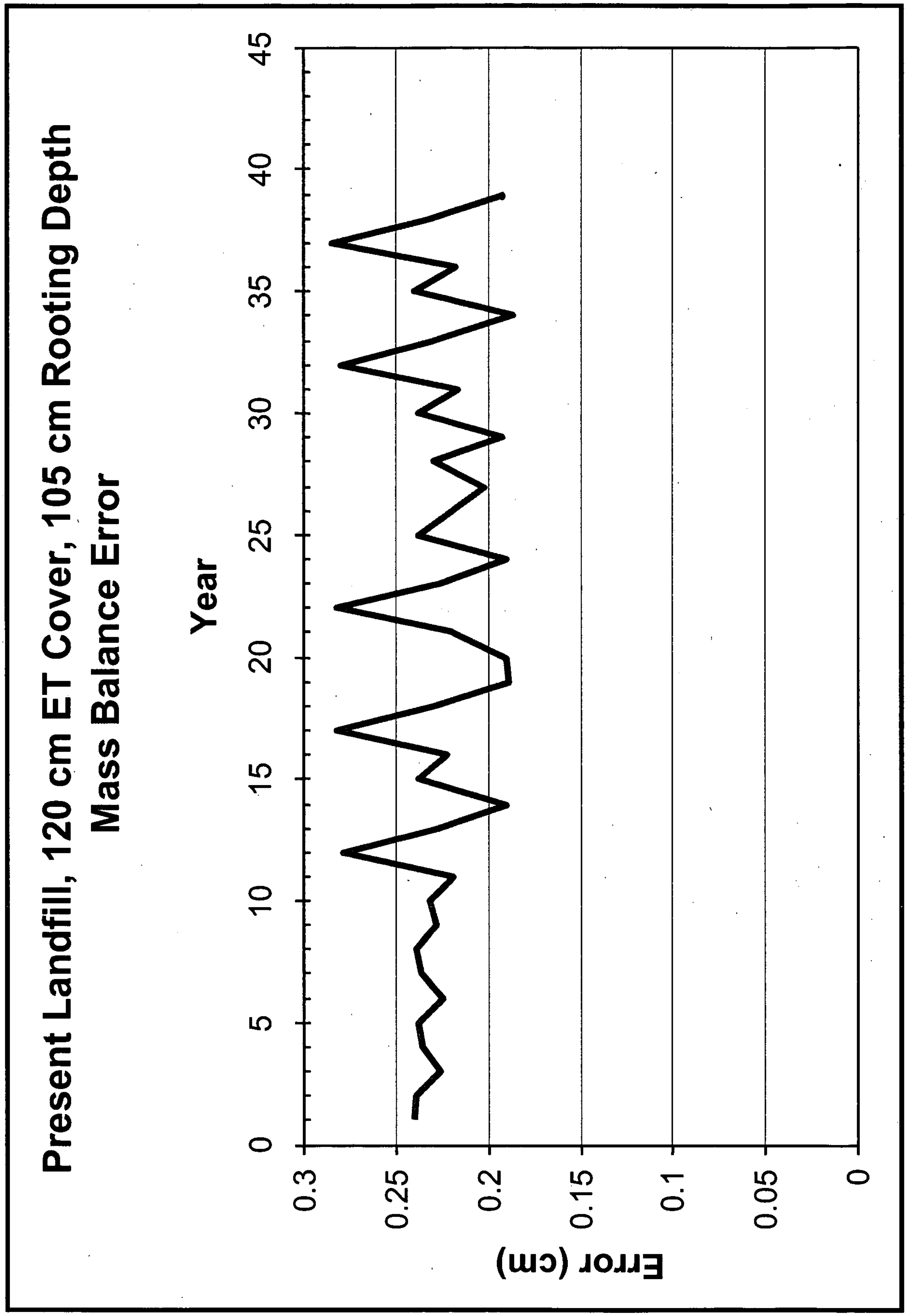

Figure A1-31

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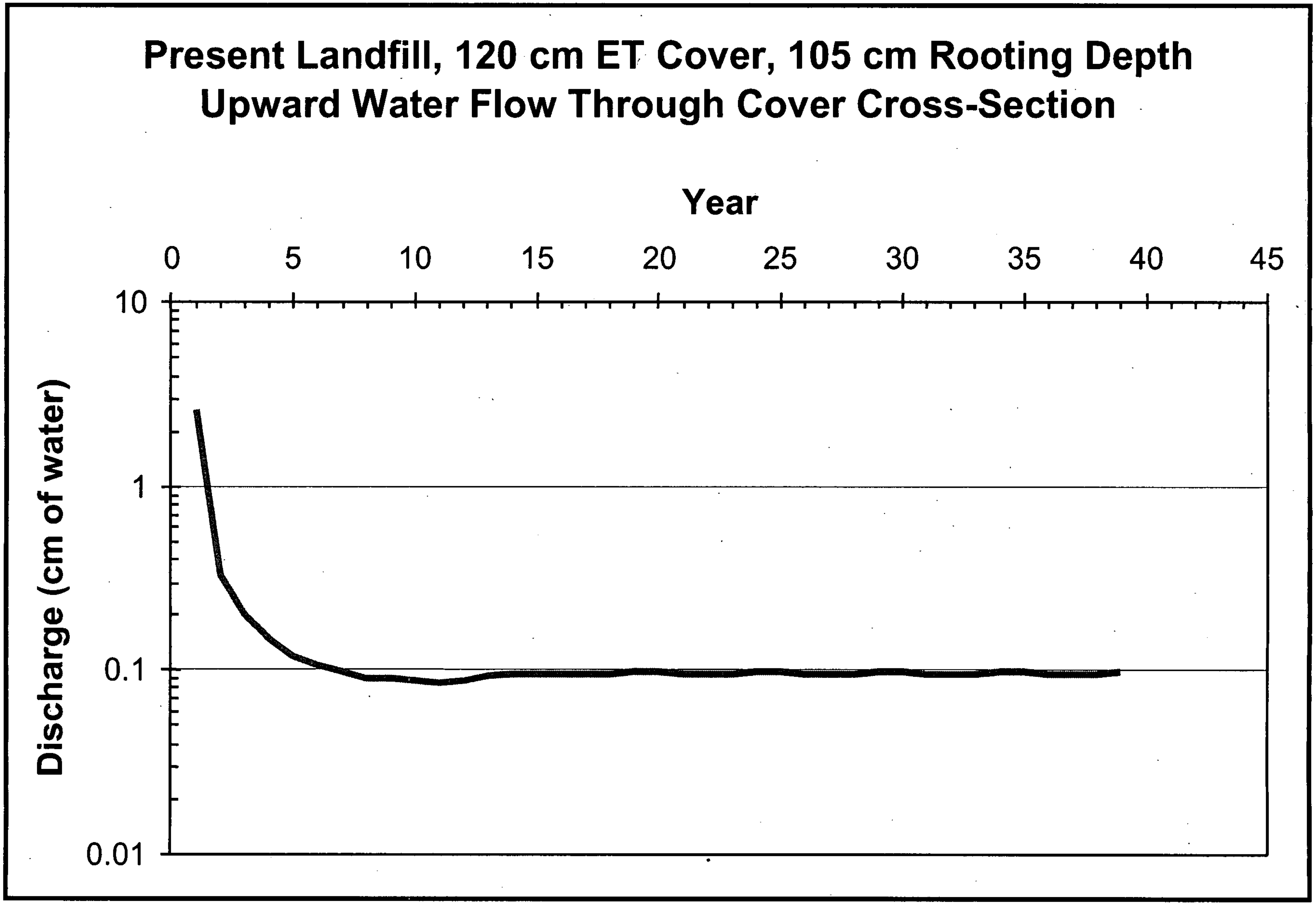
Present Landfill, 120 cm ET Cover, 105 cm Rooting Depth
Upward Water Flow Through Cover Cross-Section
Year
0
5
10
15
20
25
30
35
40
45
Discharge (cm of water)
10
1
0.1
0.01

Figure A1-32

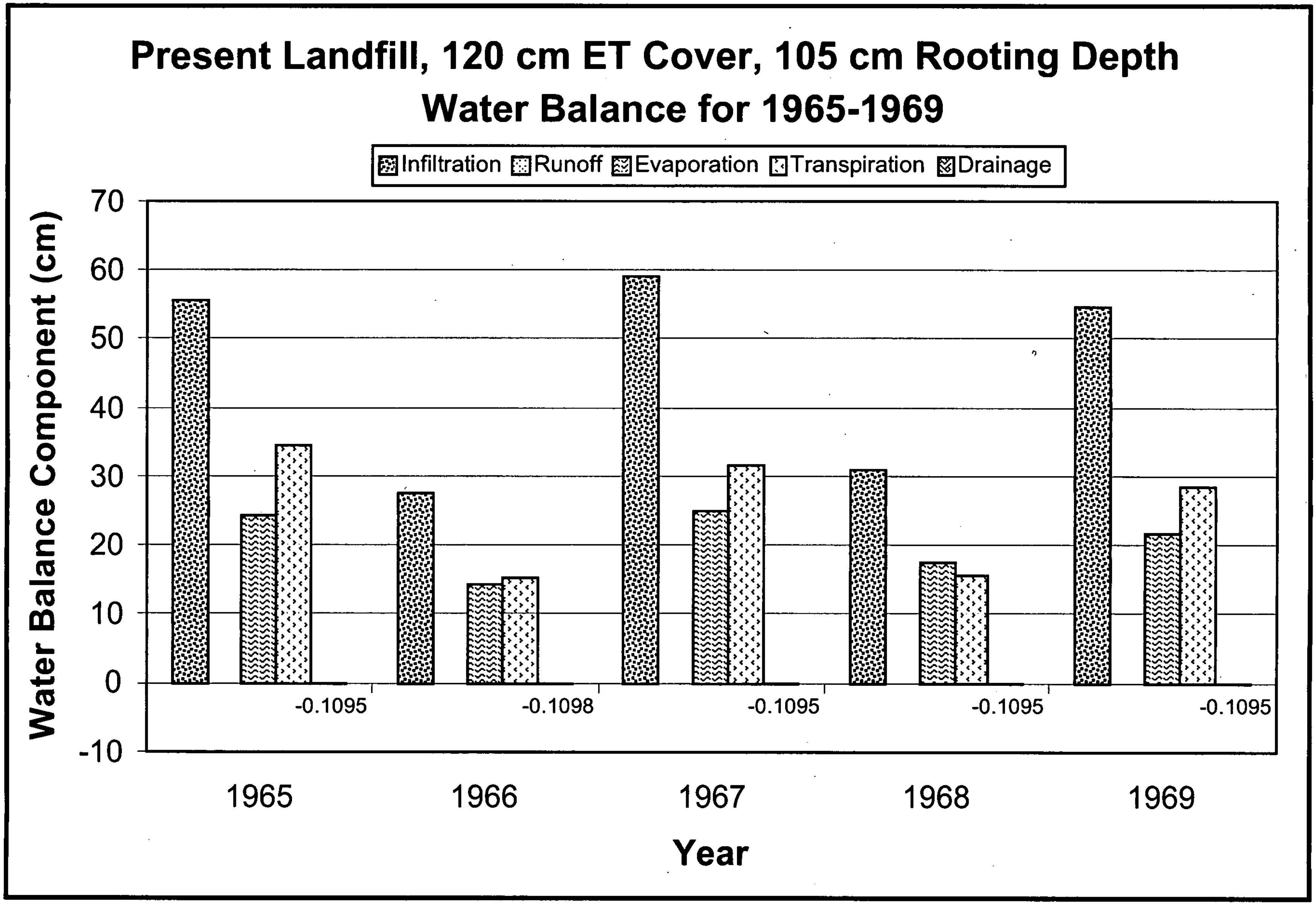
Present Landfill, 120 cm ET Cover, 105 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
-10
-0.1095
-0.1098
-0.1095
-0.1095
-0.1095
1965
1966
1967
1968
1969
Year

Figure A1-33

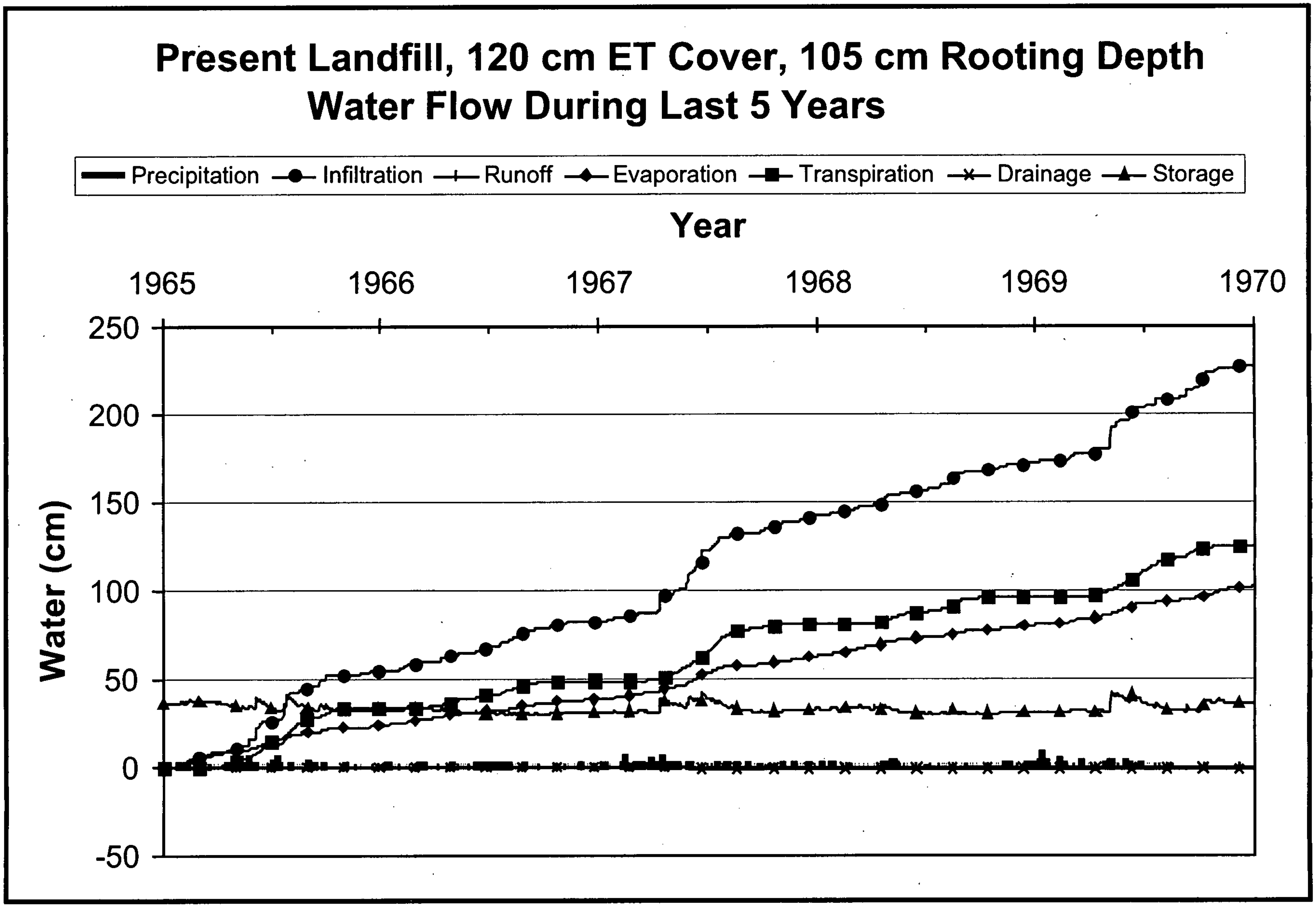
Present Landfill, 120 cm ET Cover, 105 cm Rooting Depth
Water Flow During Last 5 Years
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
250
200
150
100
50
0
-50
Water (cm)

Figure A1-34

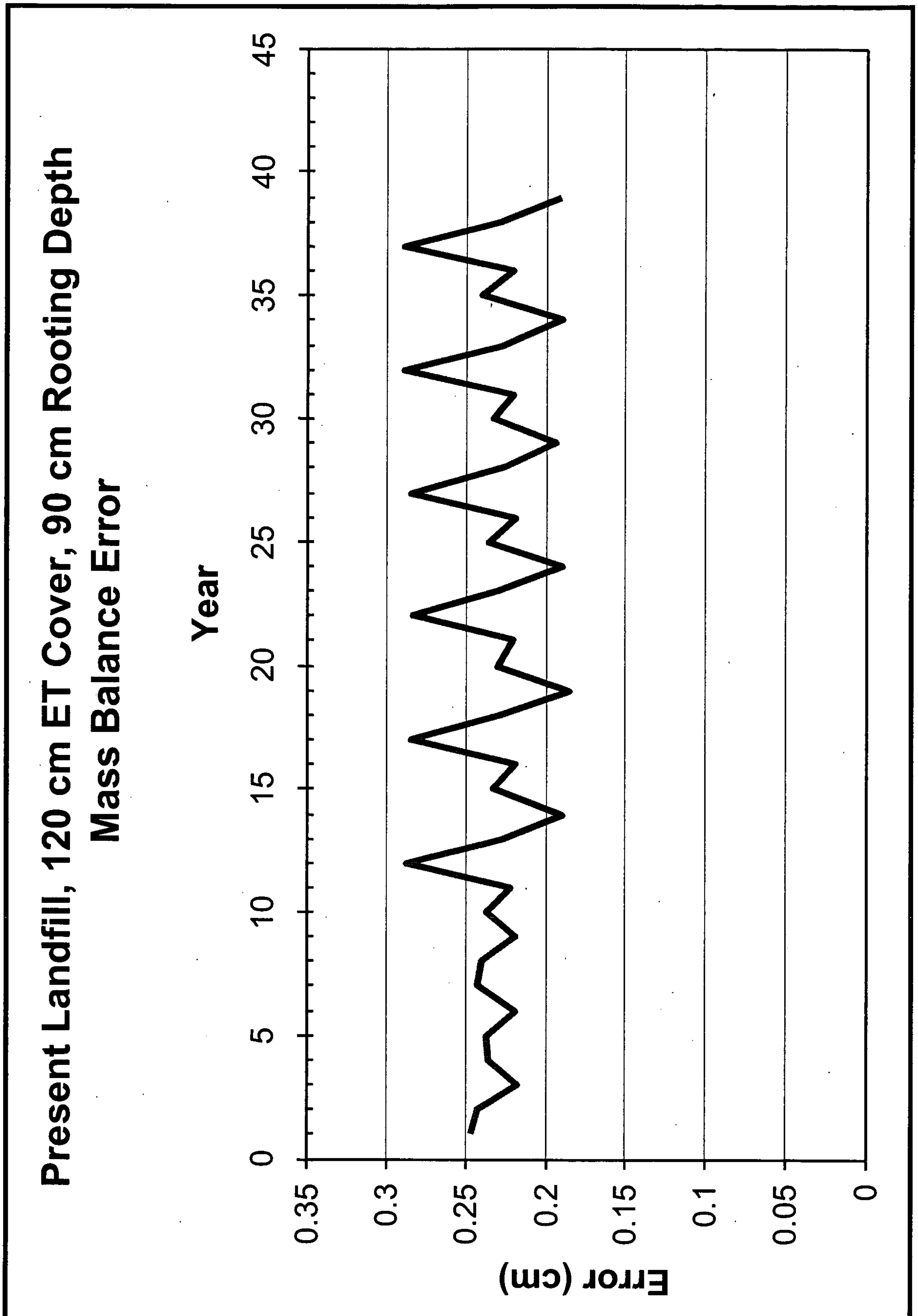

Figure A1-35

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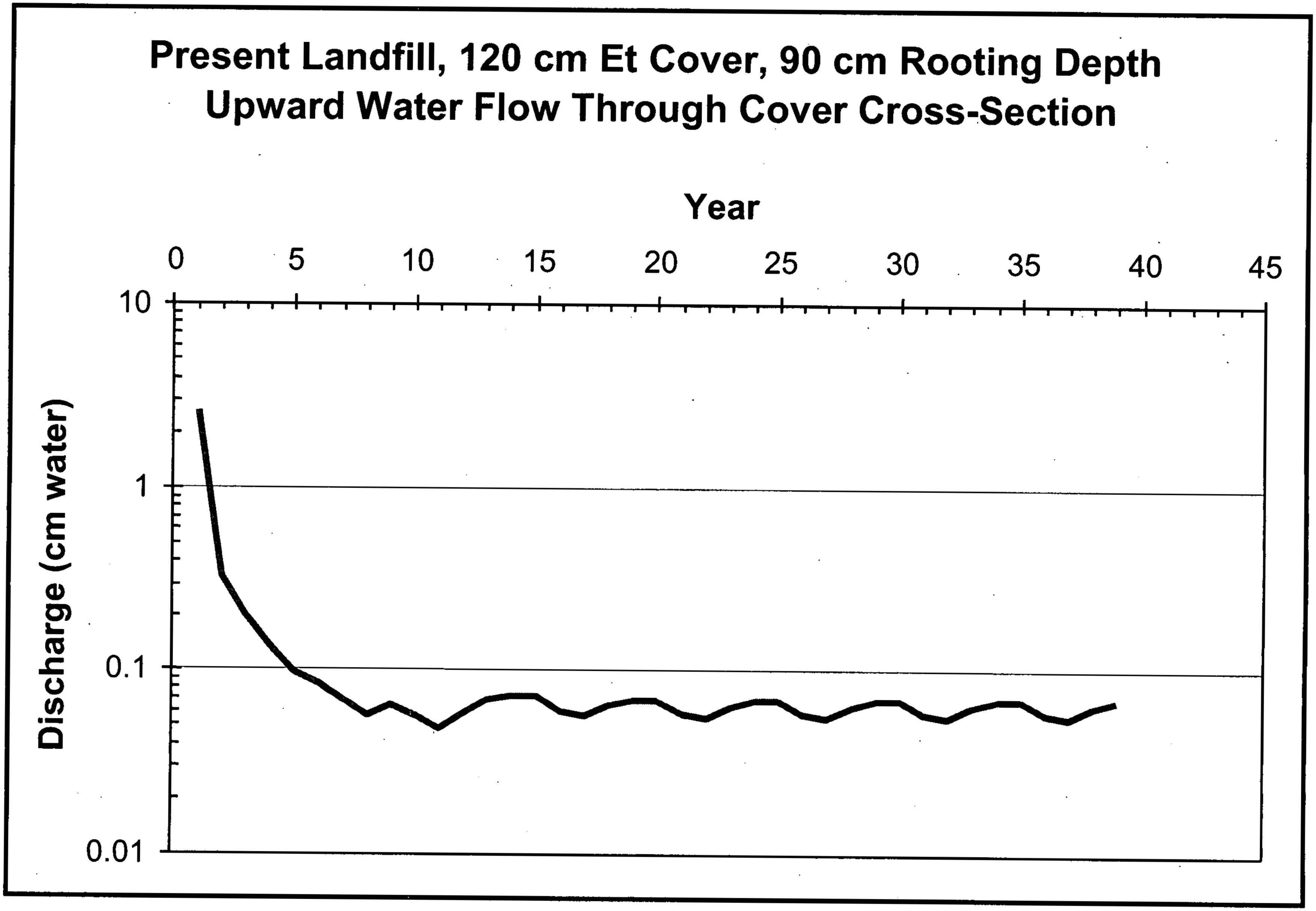

Figure A1-36

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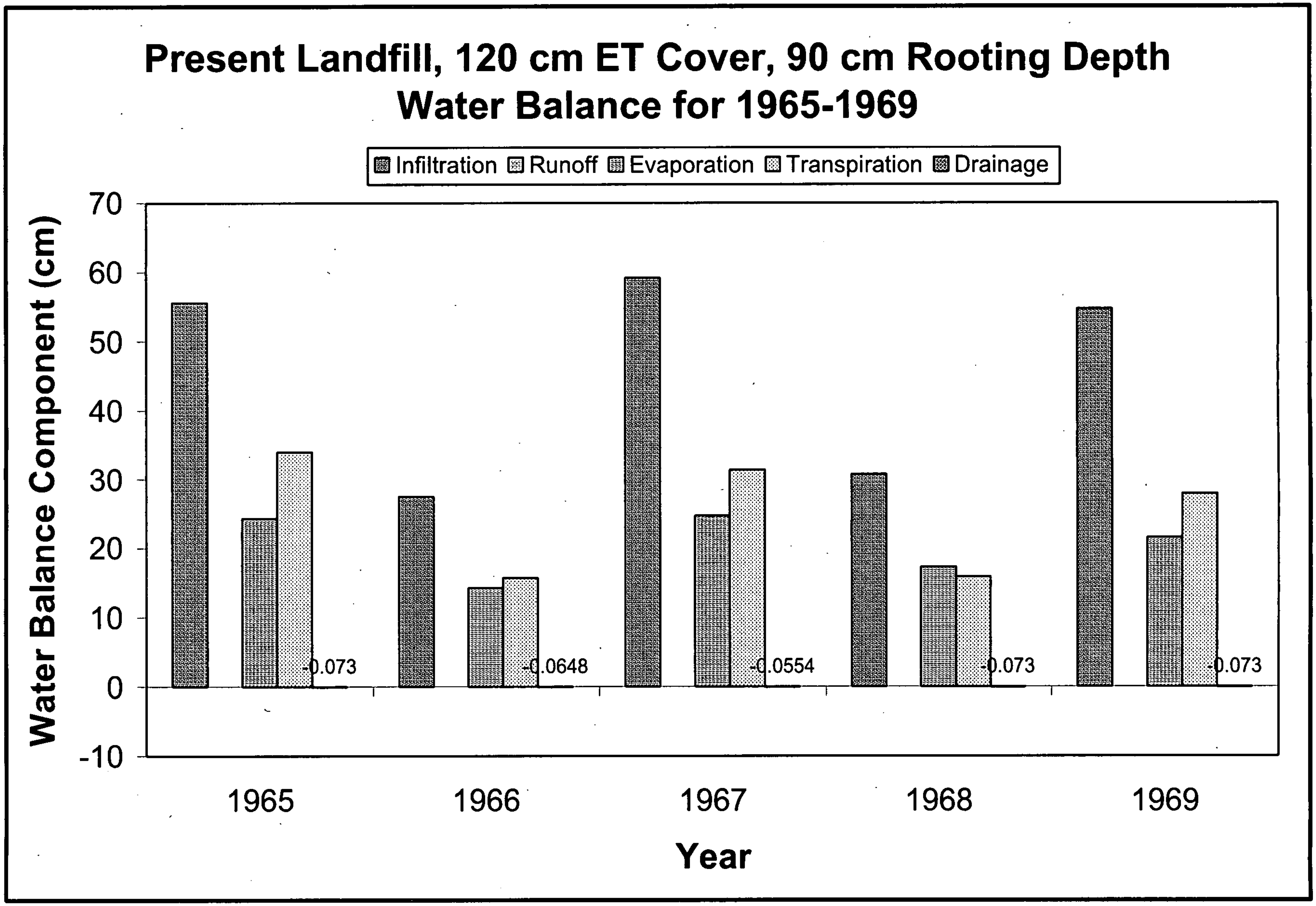

Figure A1-37

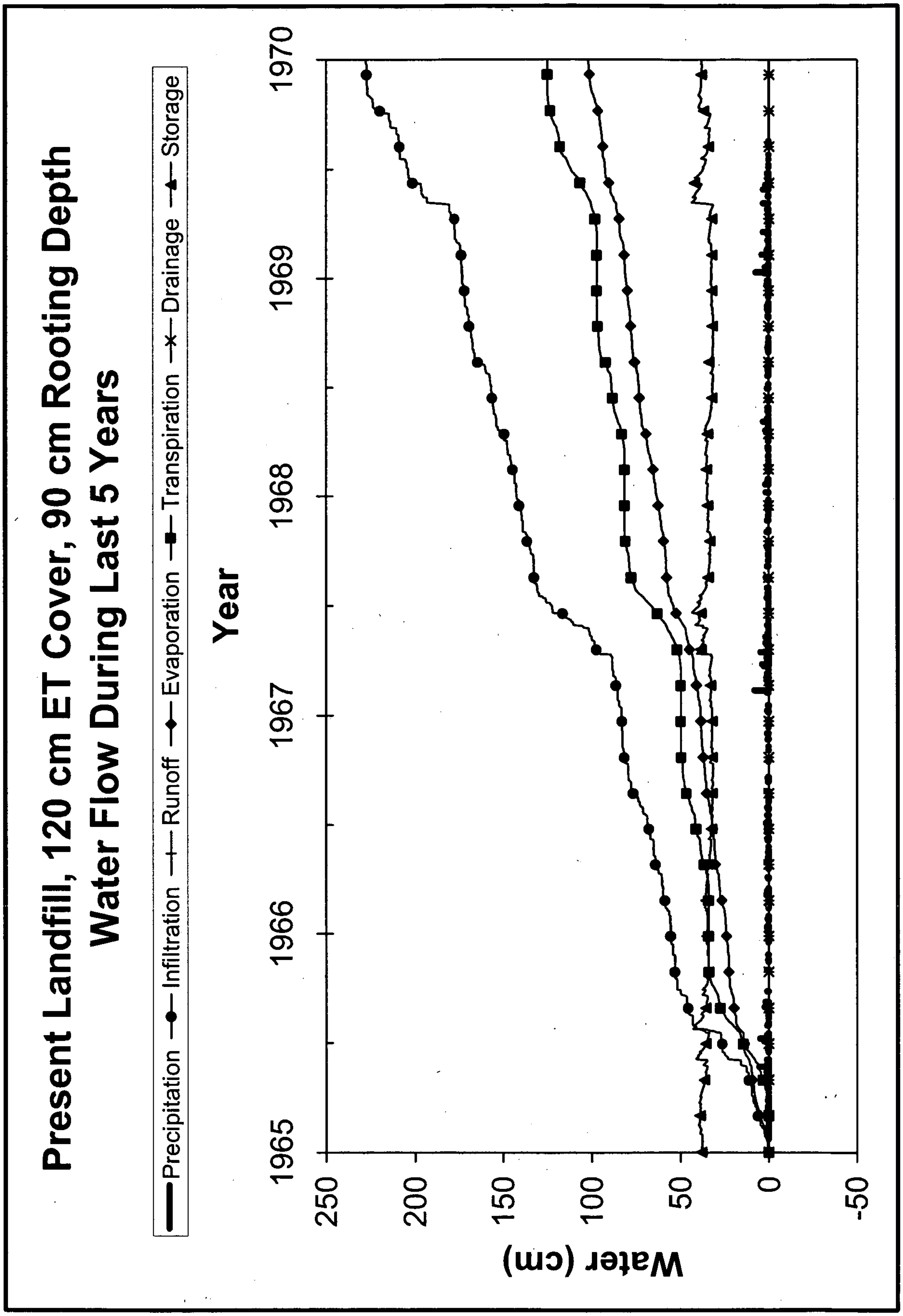

Figure A1-38

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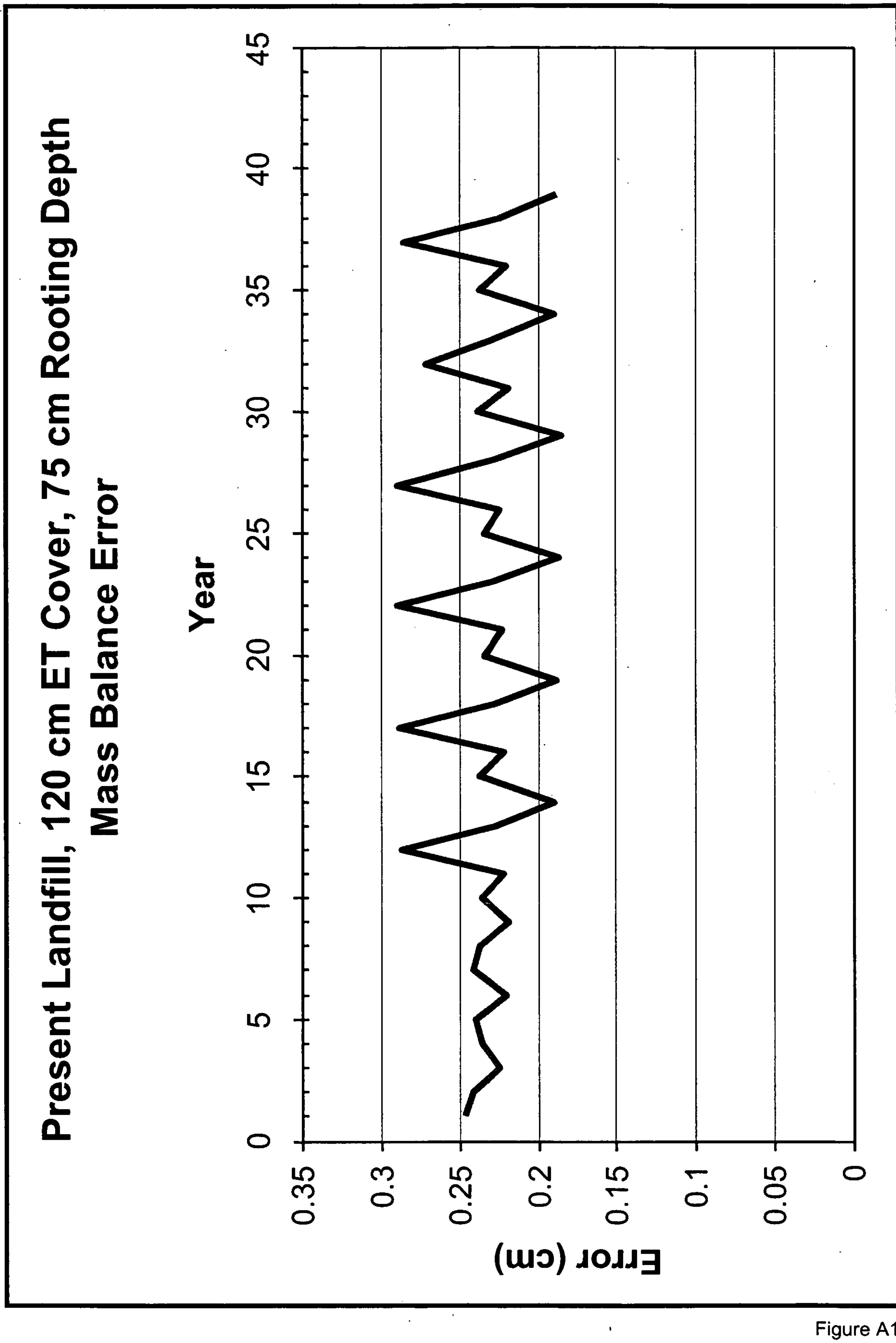

Figure A1-39

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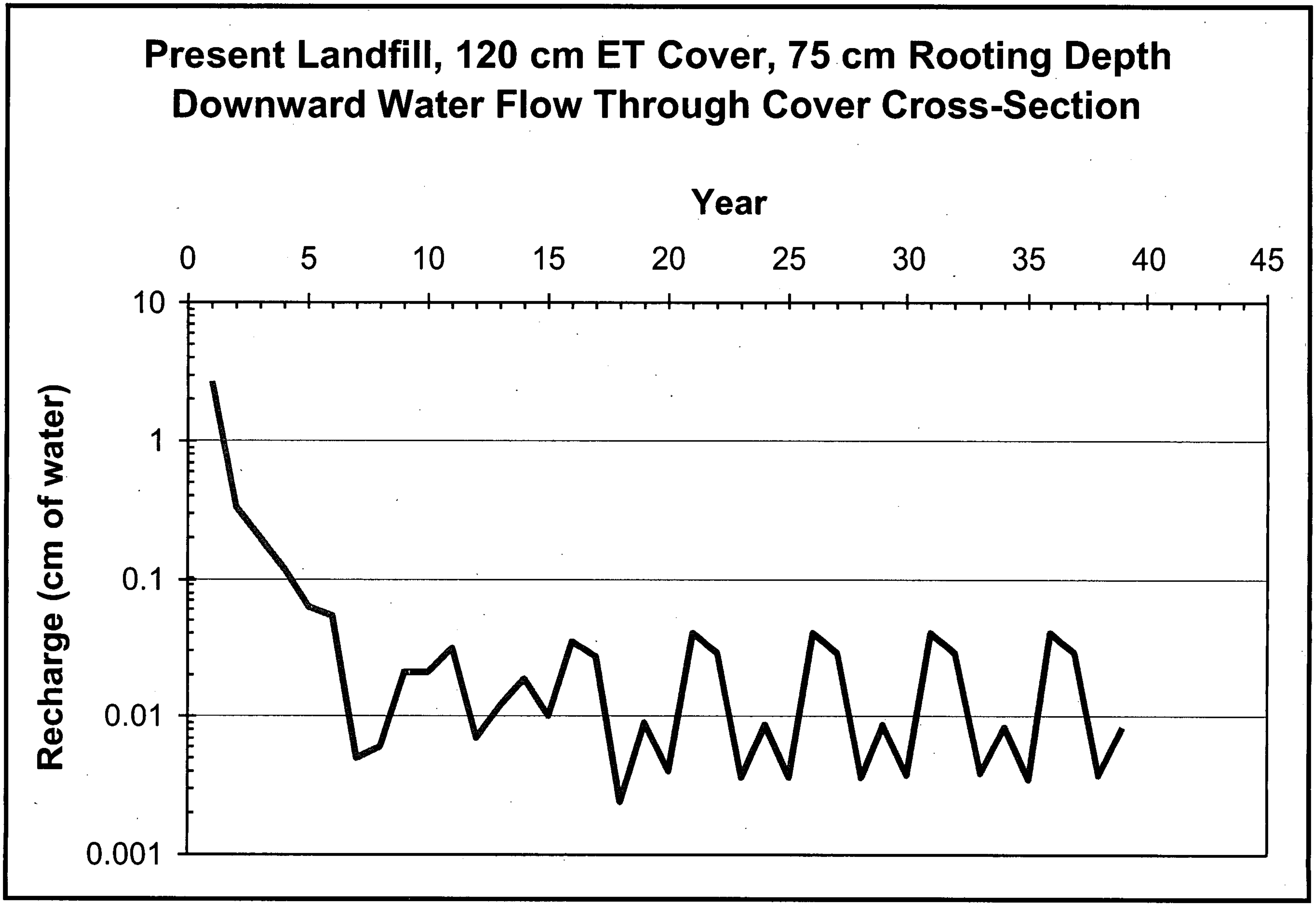

Figure A1-40

84

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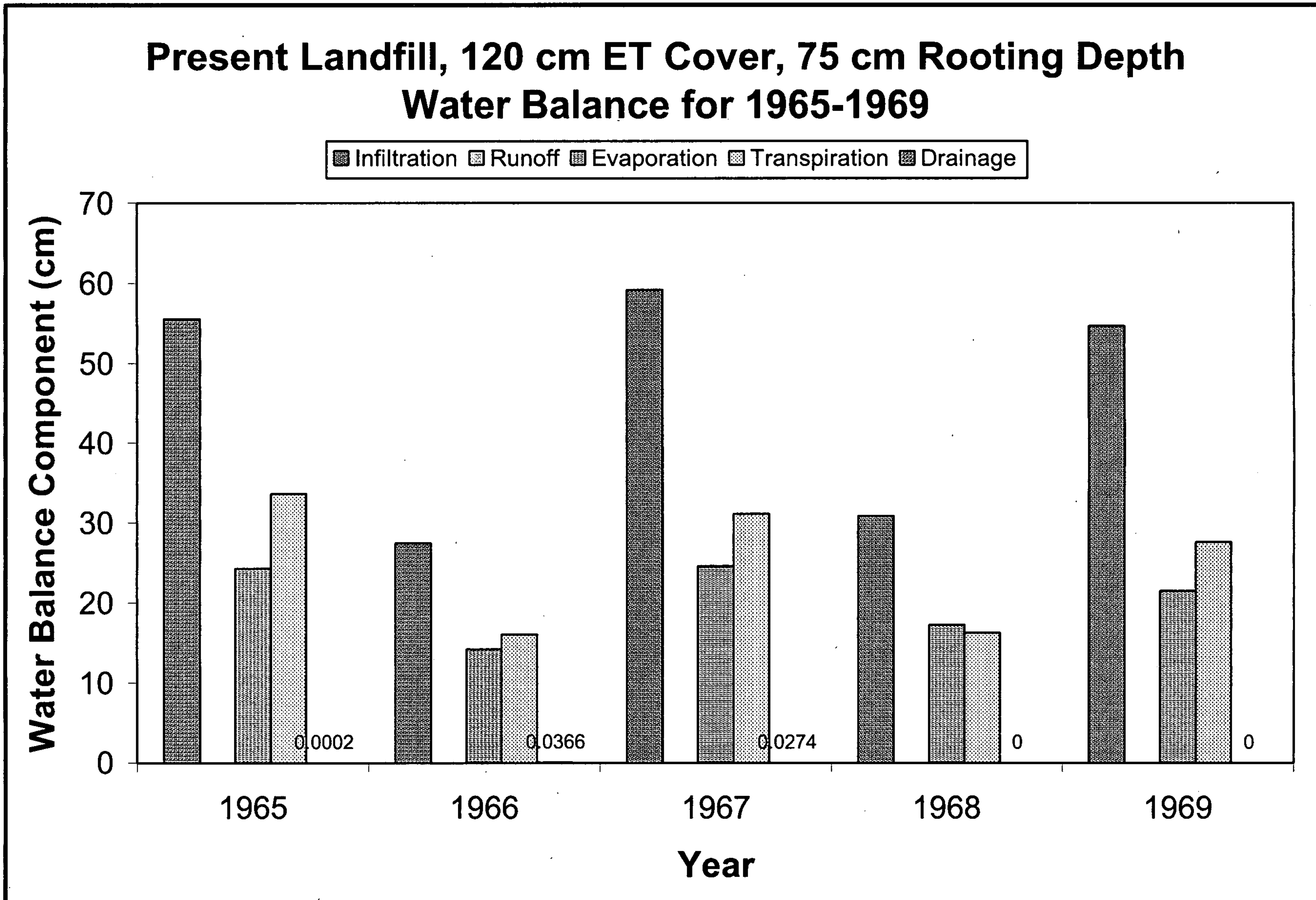

Figure A1-41

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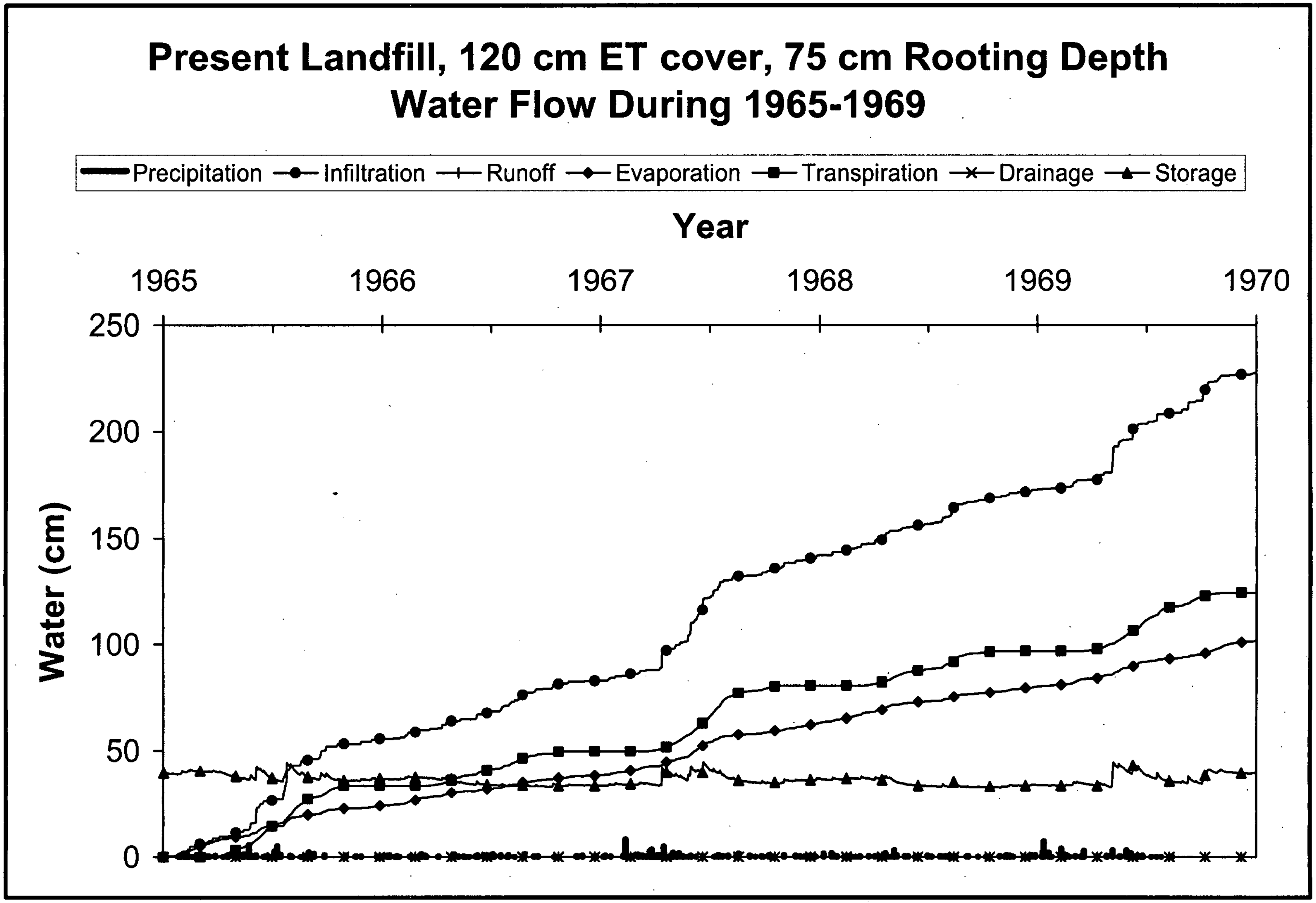

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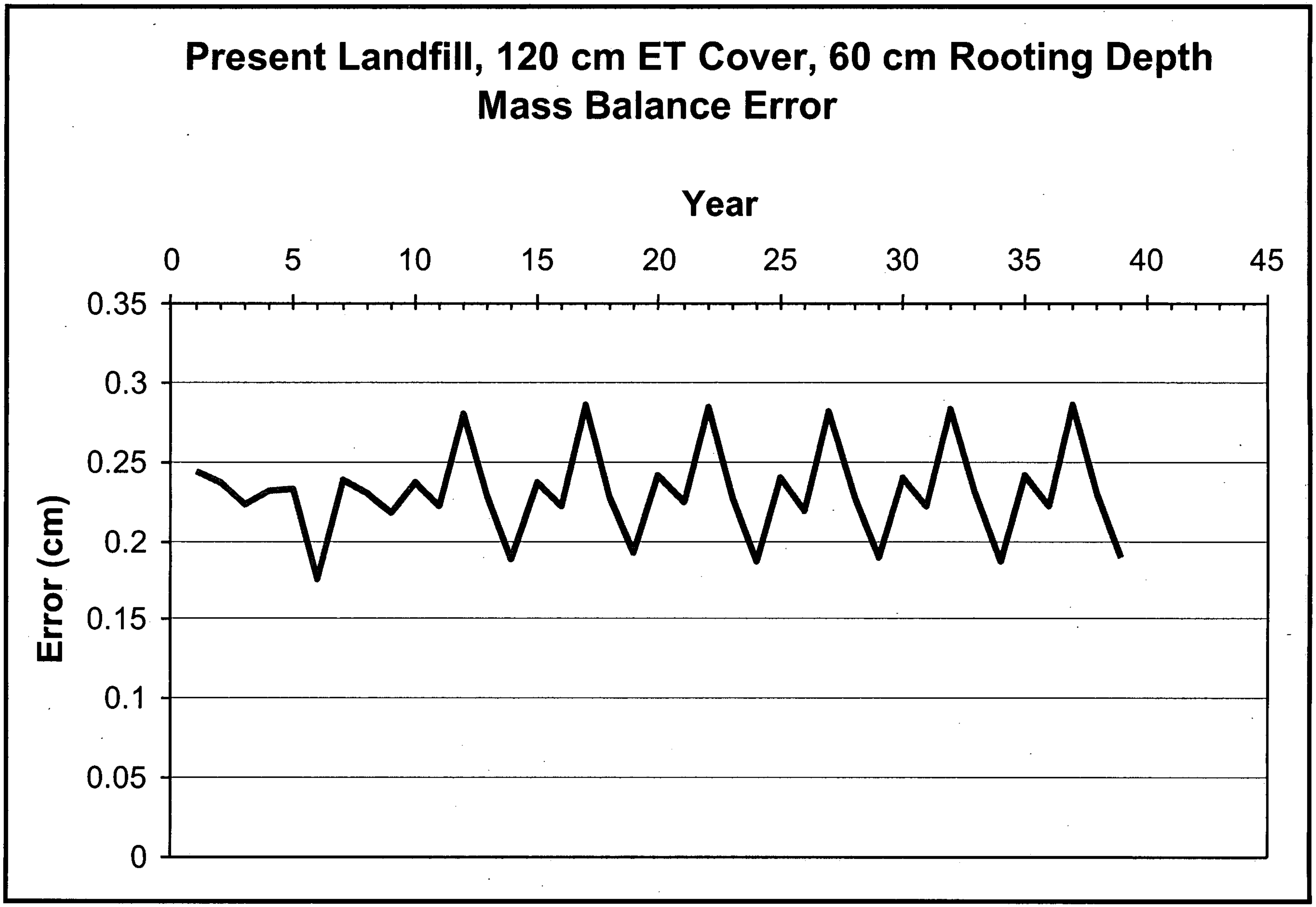

Present Landfill, 120 cm ET Cover, 60 cm Rooting Depth
Mass Balance Error
Year
0
5
10
15
20
25
30
35
40
45
Error (cm)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-43

Present Landfill, 120 cm ET Cover, 60 cm Rooting Depth
Downward Water Flow Through Cover Cross-Section

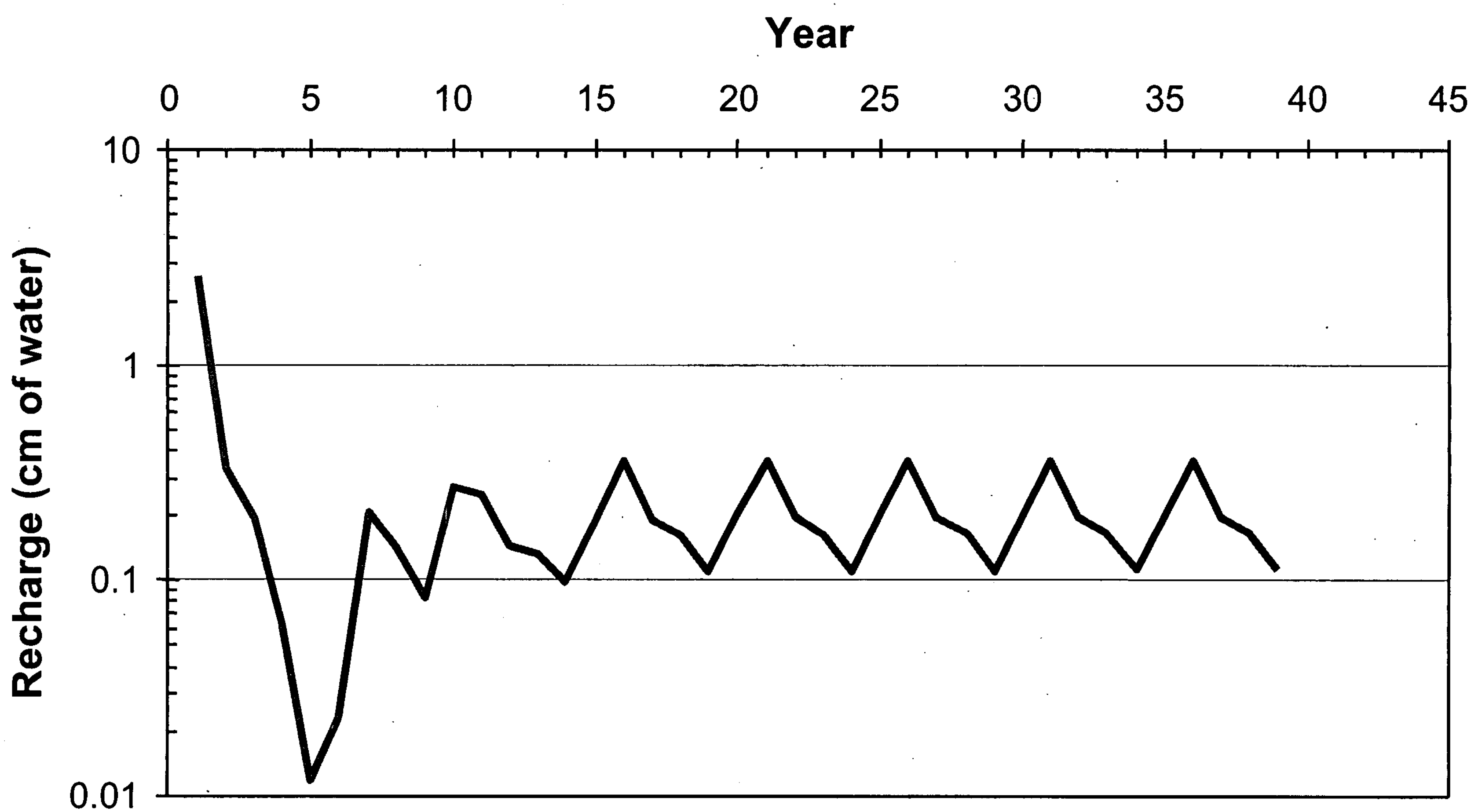

Figure A1-44

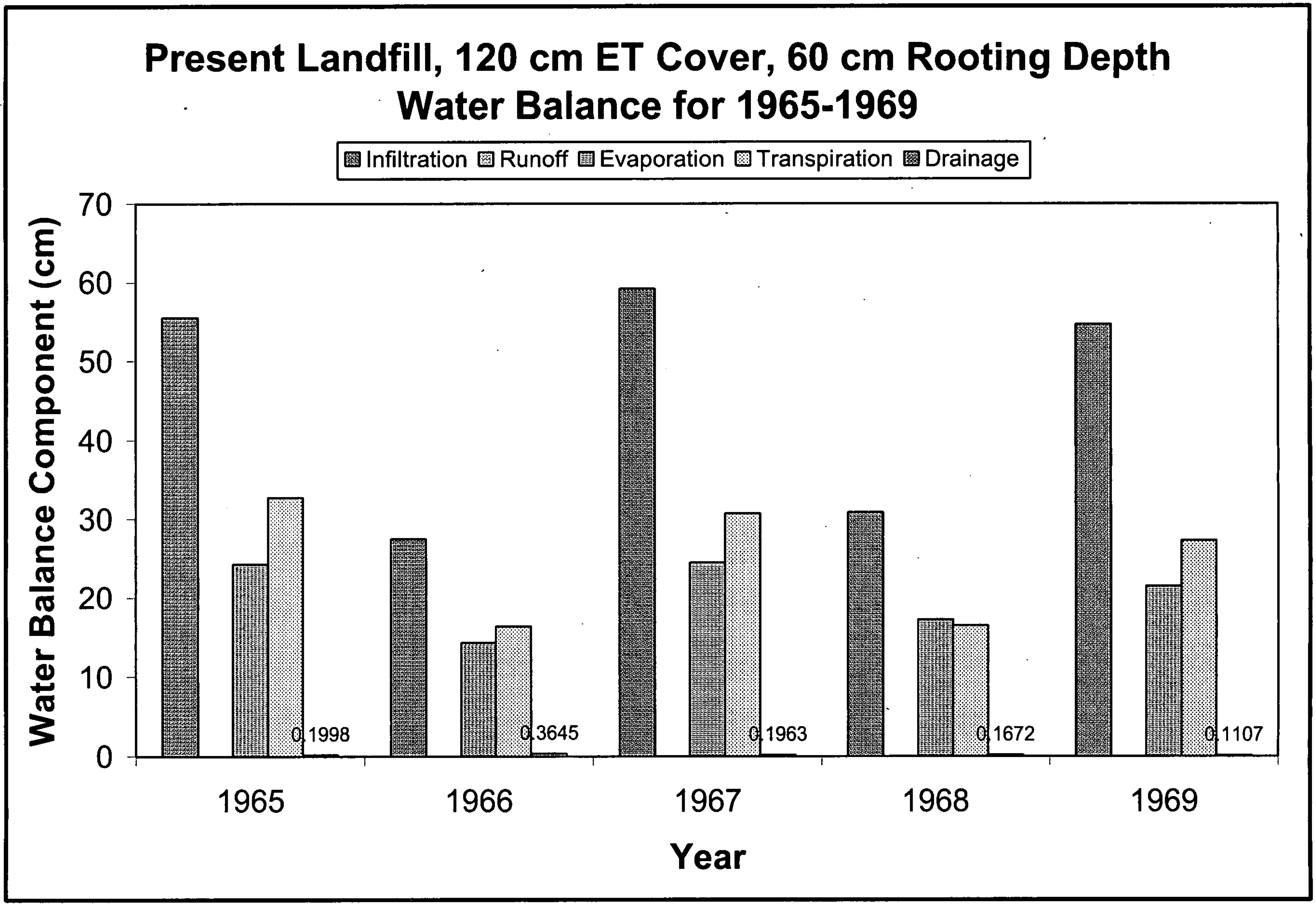
Present Landfill, 120 cm ET Cover, 60 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
0
10
20
30
40
50
60
70
0.1998
0.3645
0.1963
0.1672
0.1107
1965
1966
1967
1968
1969
Year

Figure A1-45

Present Landfill, 120 cm ET Cover, 60 cm Rooting Depth
Water Flow During 1965-1969

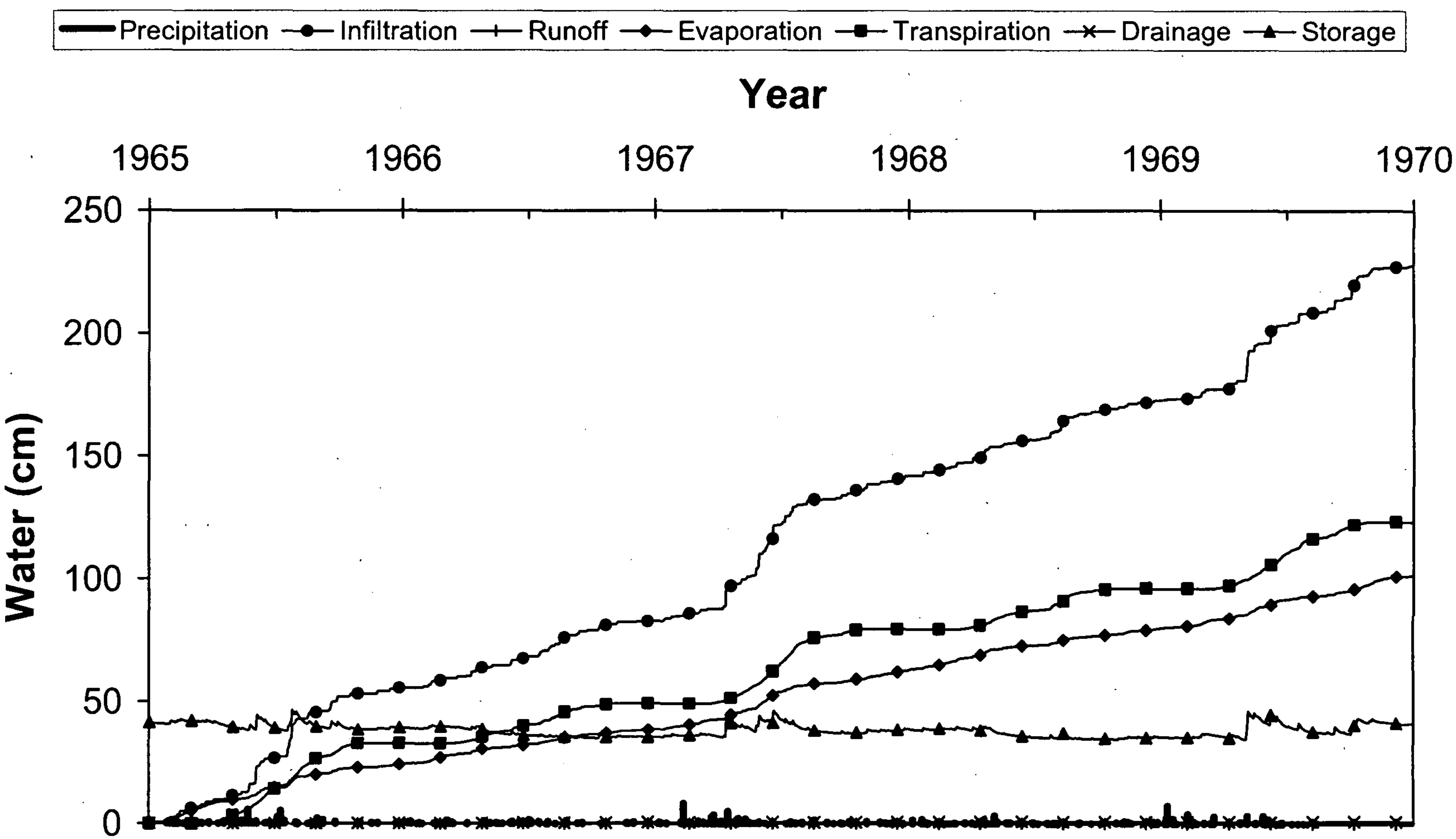

Figure A1-46

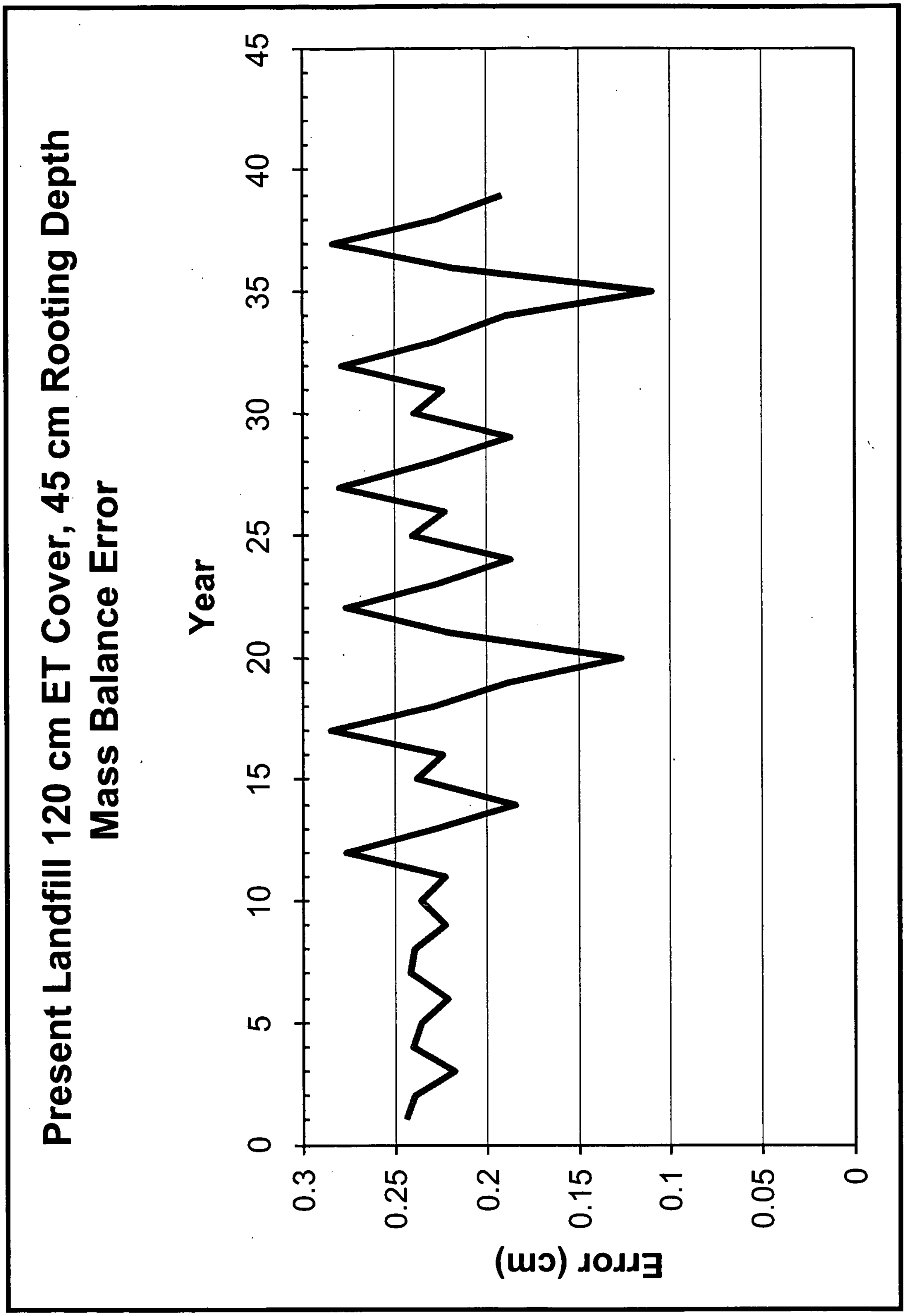

Figure A1-47

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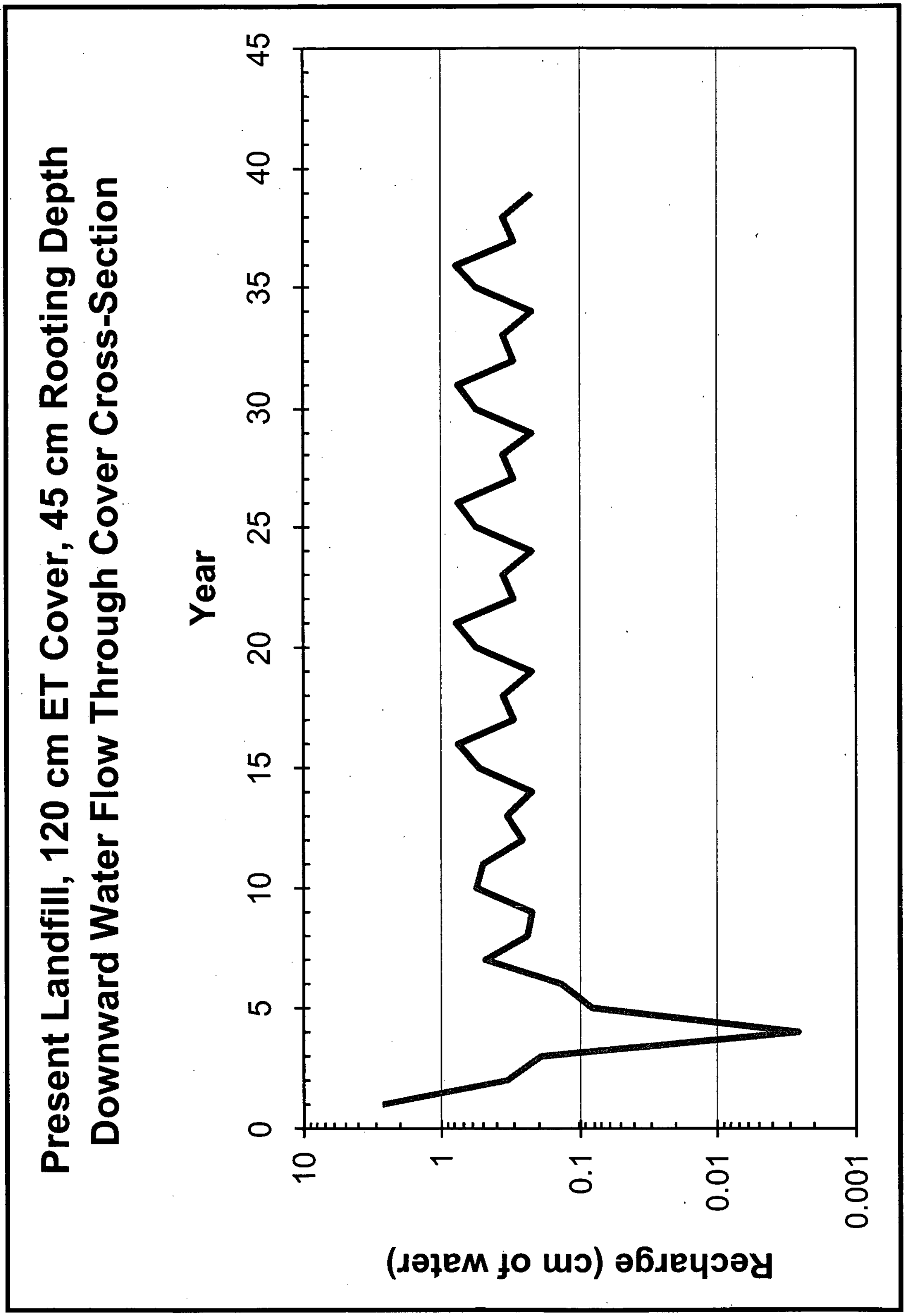


Figure A1-48

92

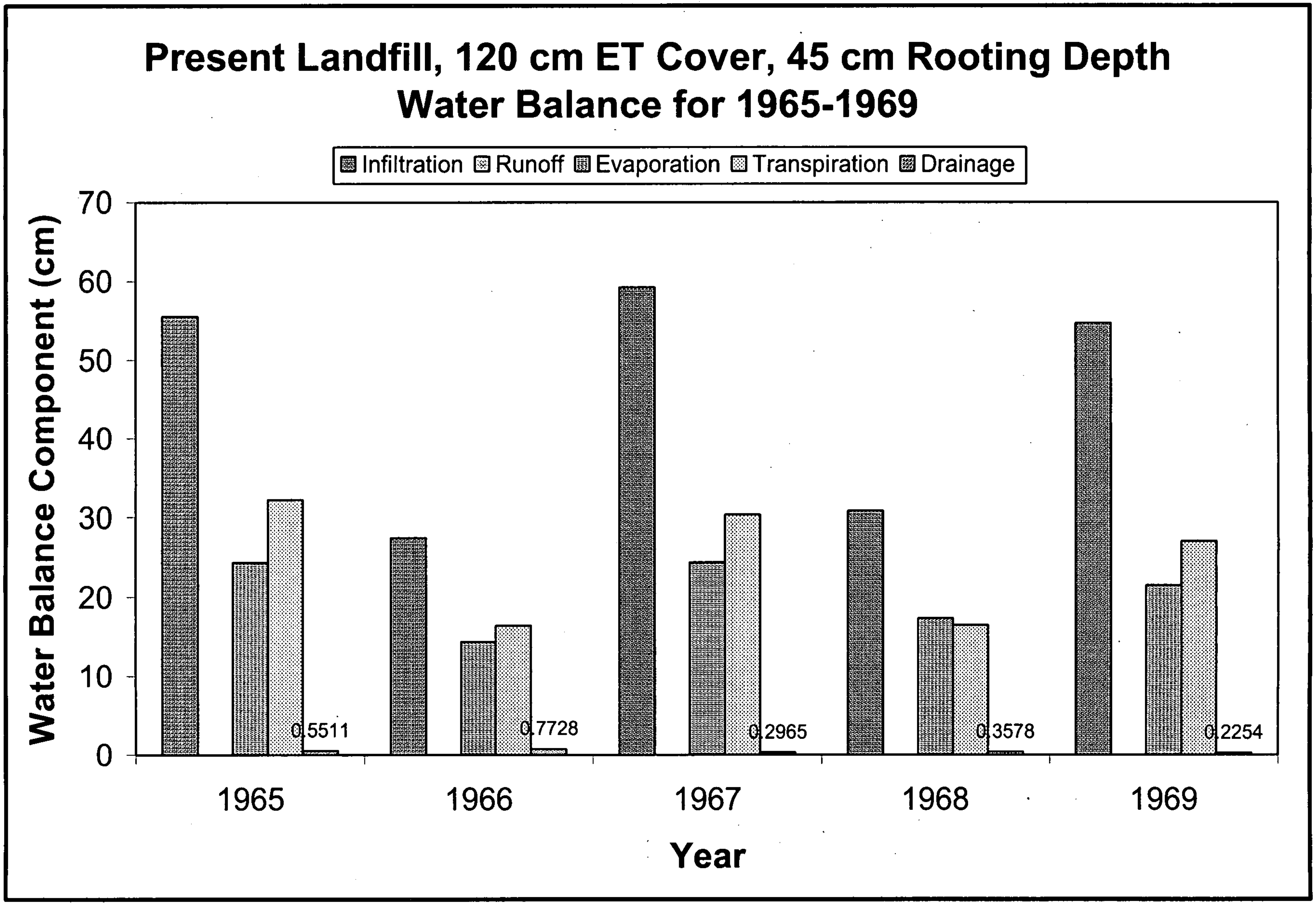

Present Landfill, 120 cm ET Cover, 45 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
0.5511
0.7728
0.2965
0.3578
0.2254
1965
1966
1967
1968
1969
Year

Figure A1-49

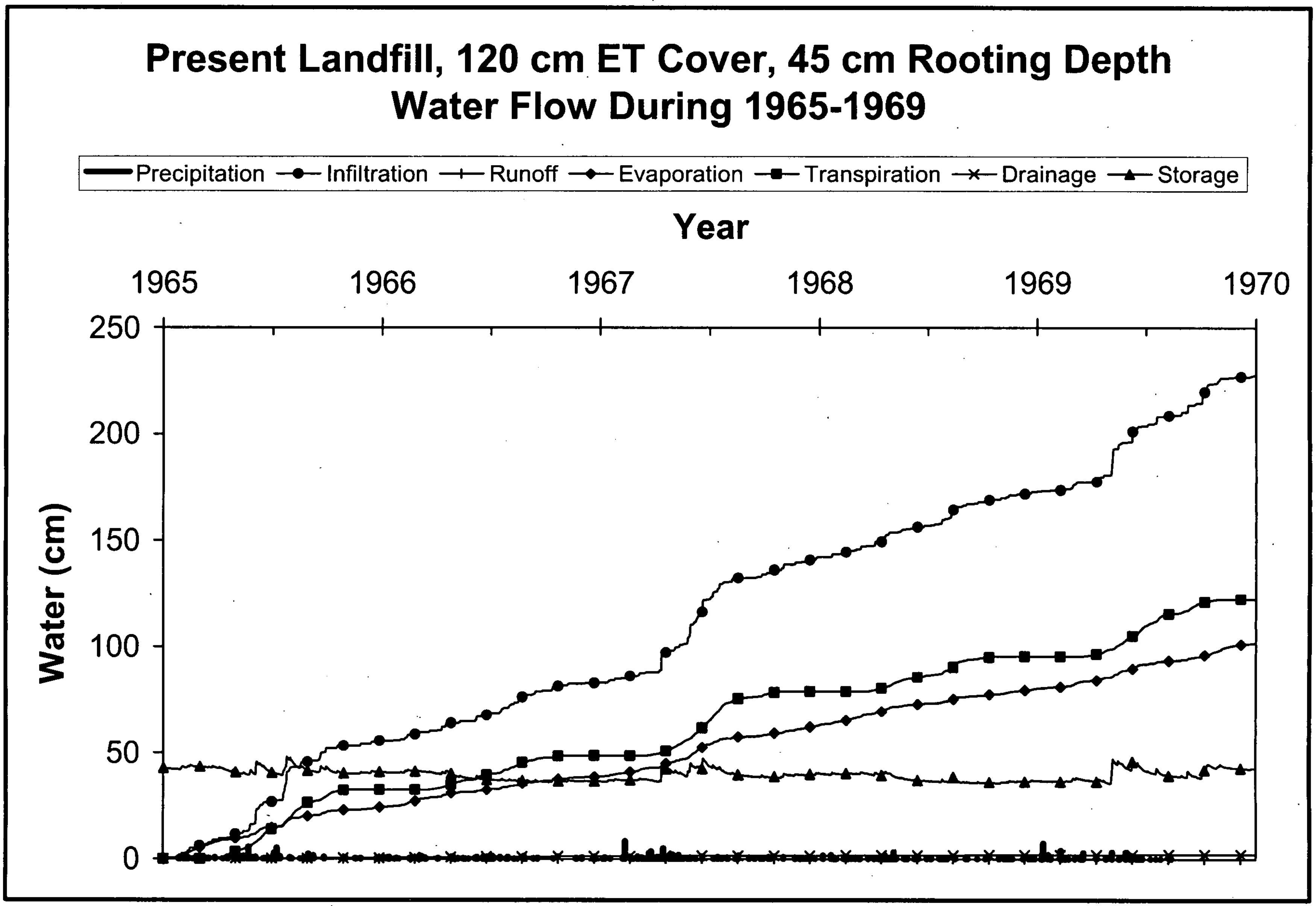

Present Landfill, 120 cm ET Cover, 45 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
250
200
150
100
50
0
Water (cm)

Figure A1-50

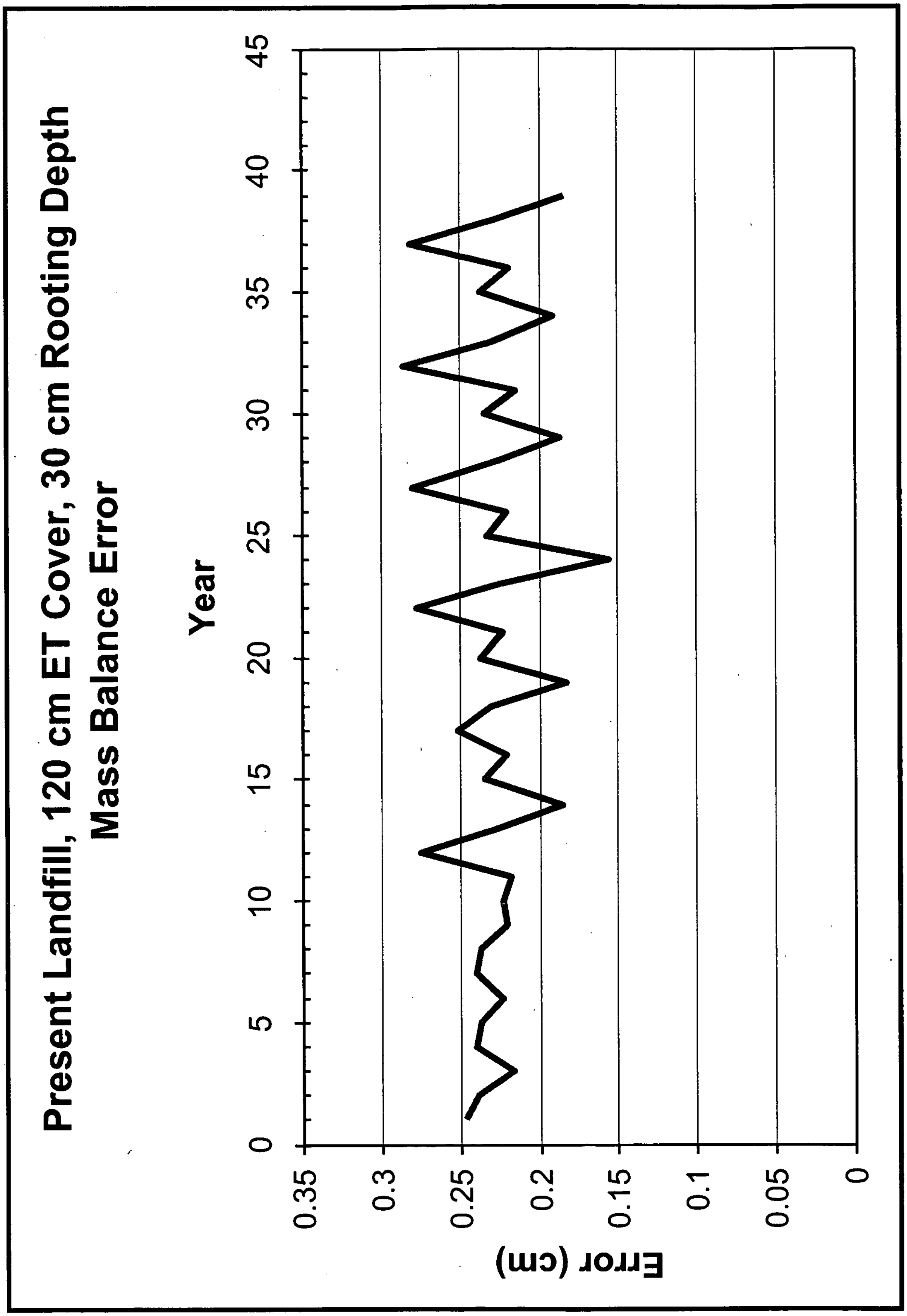
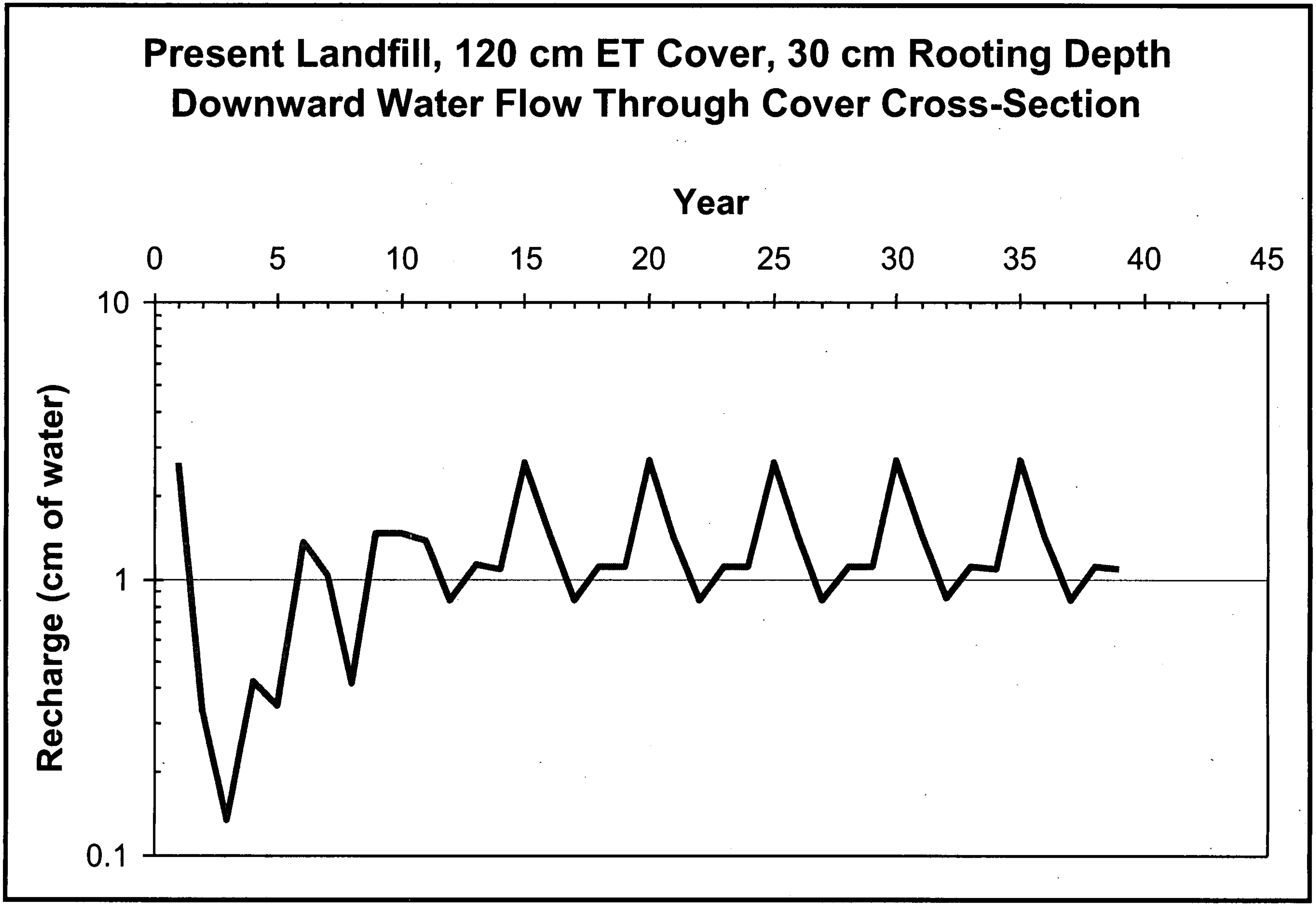


Figure A1-51

95



Present Landfill, 120 cm ET Cover, 30 cm Rooting Depth
Downward Water Flow Through Cover Cross-Section
Year
0
5
10
15
20
25
30
35
40
45
10
1
0.1
Recharge (cm of water)

Figure A1-52

Present Landfill, 120 cm ET Cover, 30 cm Rooting Depth Water Balance for 1965-1969

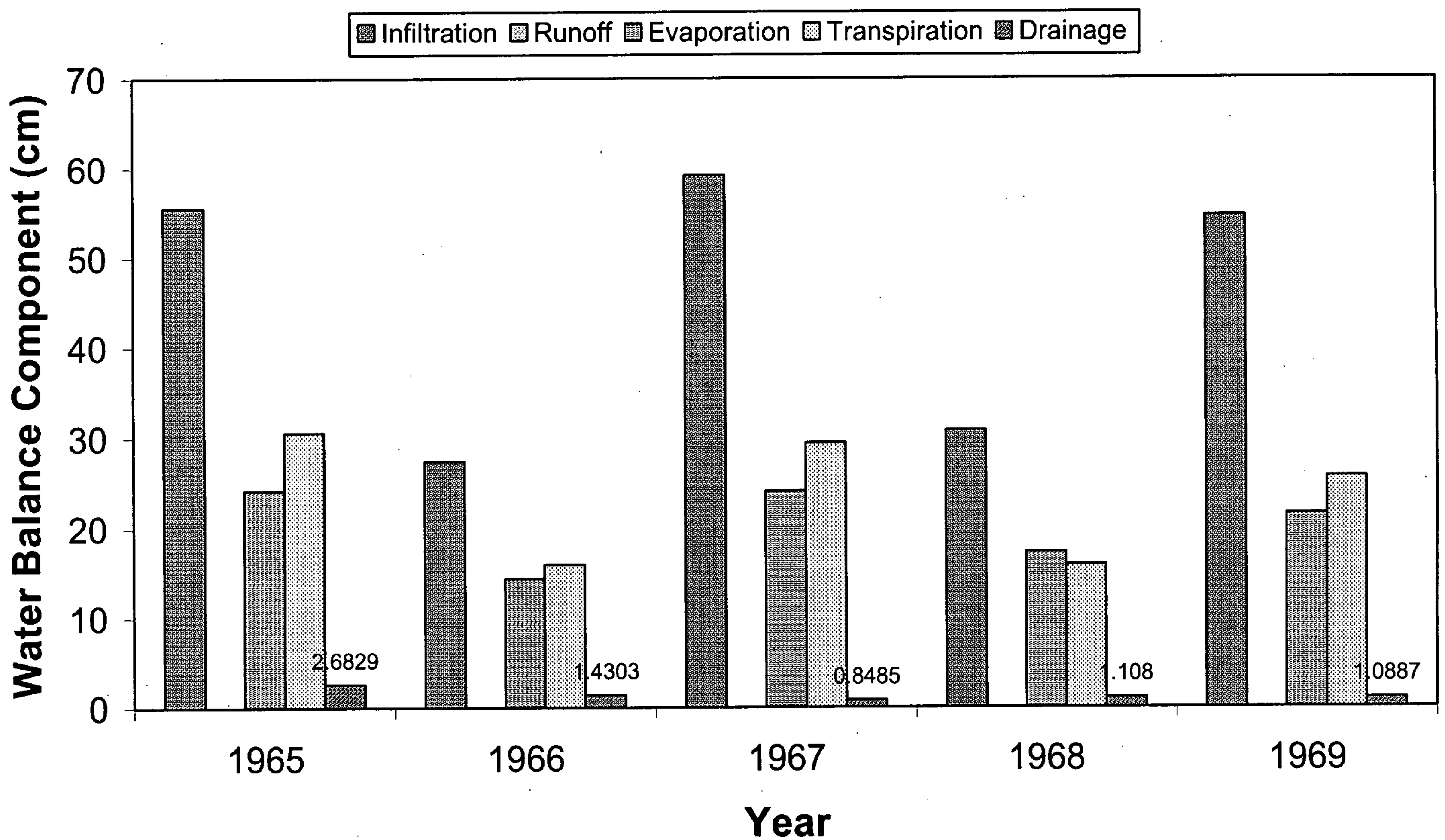


Figure A1-53

98

Present Landfill, 120 cm ET Cover, 30 cm Rooting Depth
Water Flow During 1965-1969

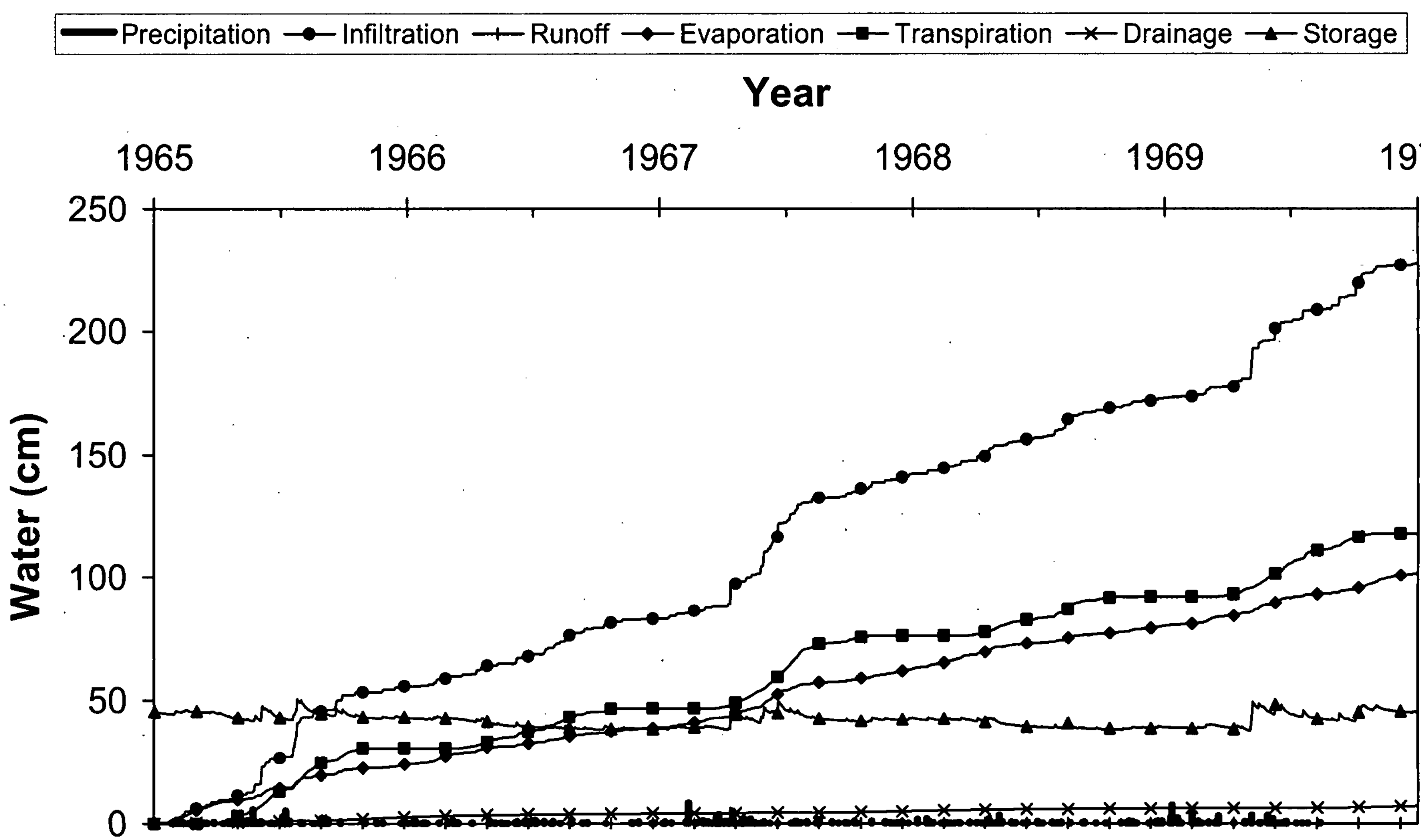


Figure A1-54

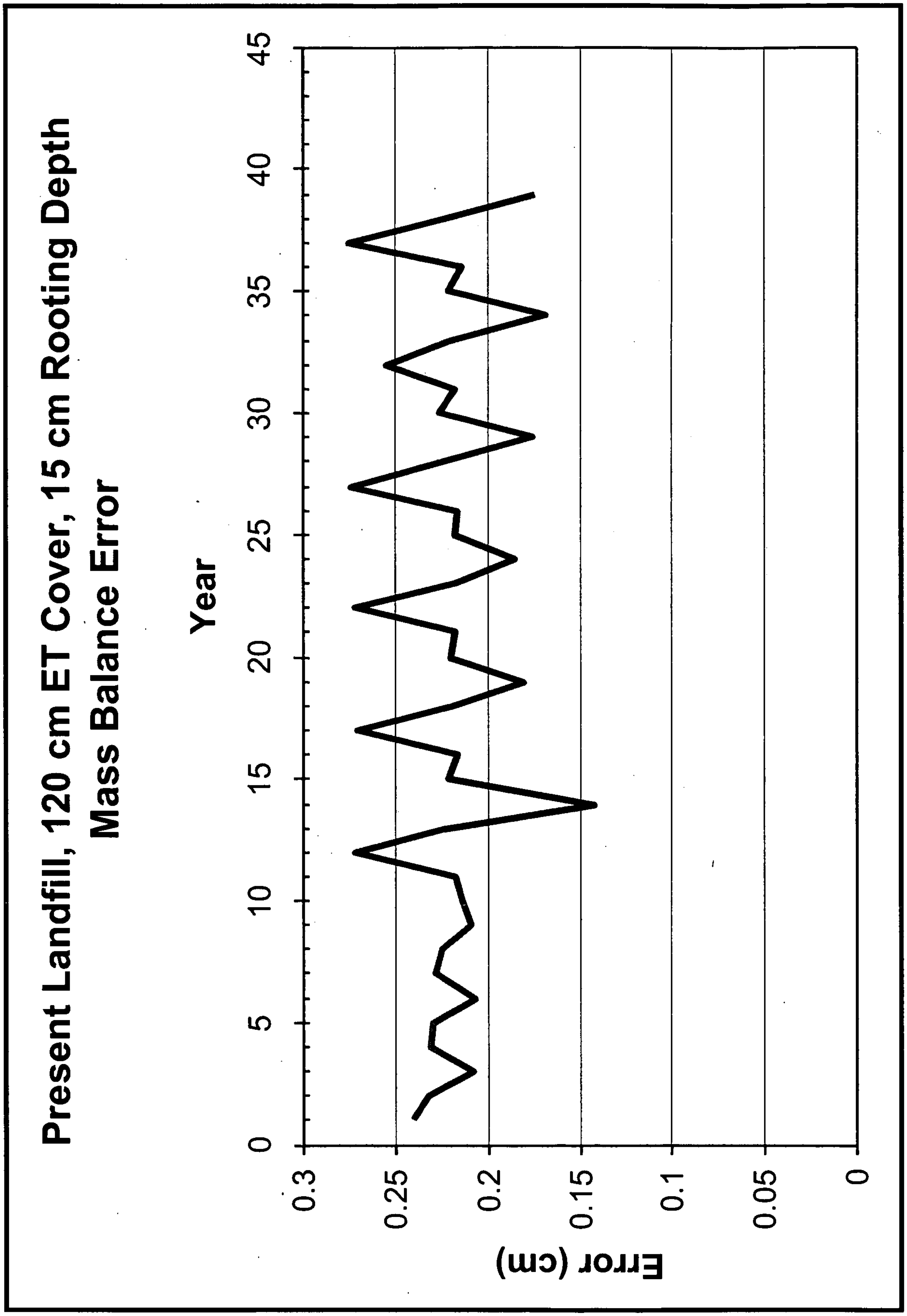

Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
Mass Balance Error
Year
Error (cm)
0
5
10
15
20
25
30
35
40
45
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-55

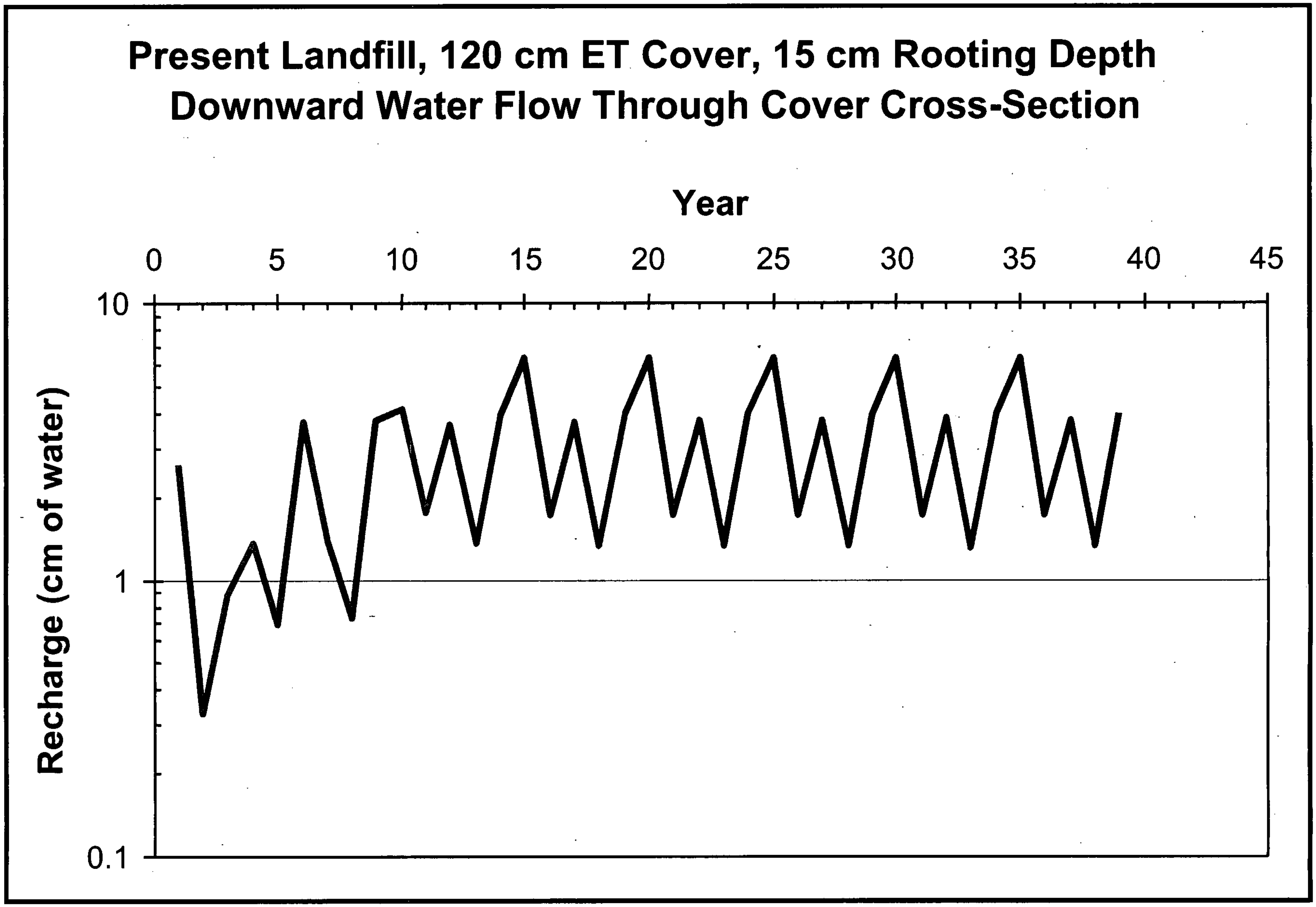
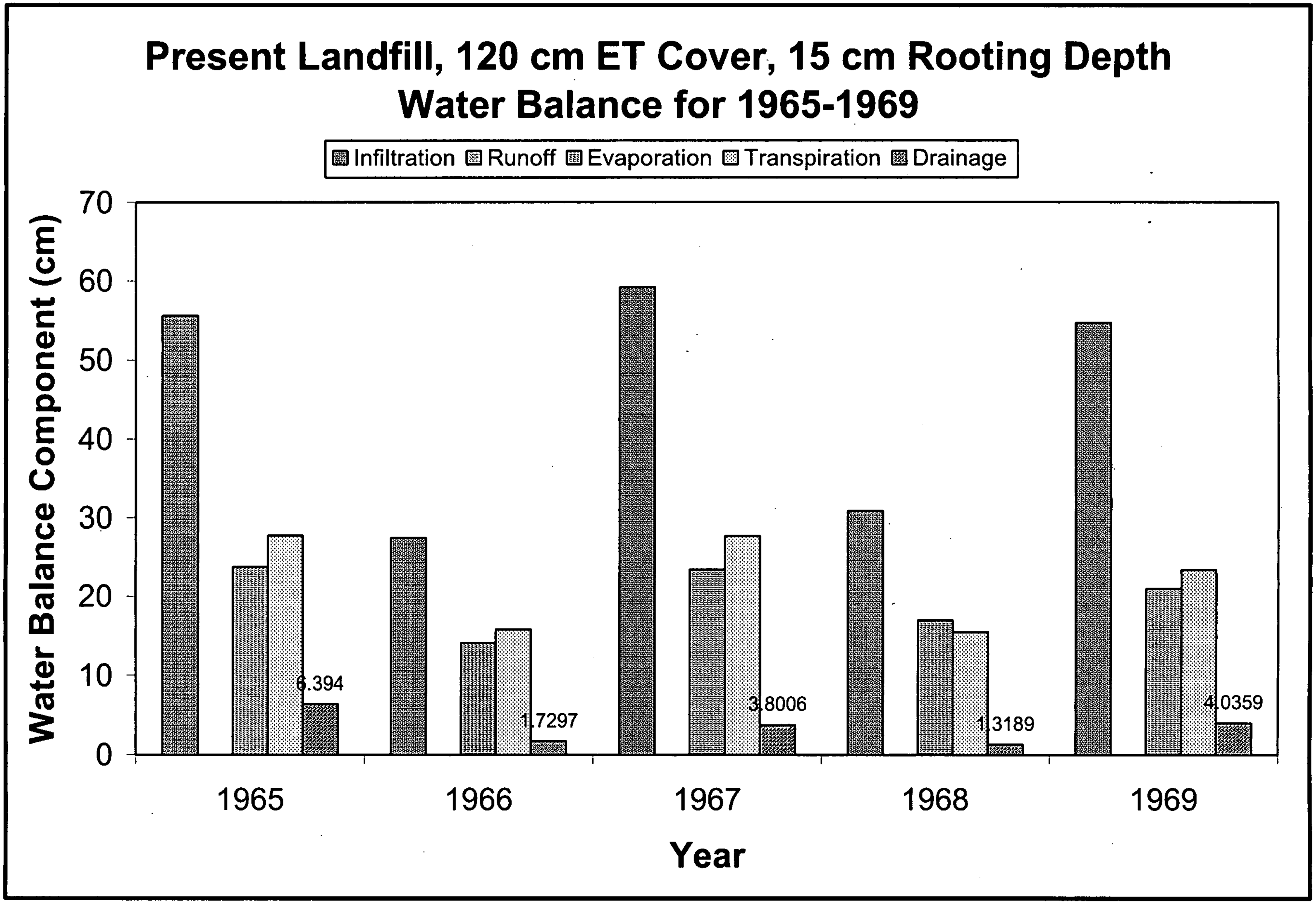


Figure A1-56

100



Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
6.394
1.7297
3.8006
1.3189
4.0359
1965
1966
1967
1968
1969
Year

Figure A1-57

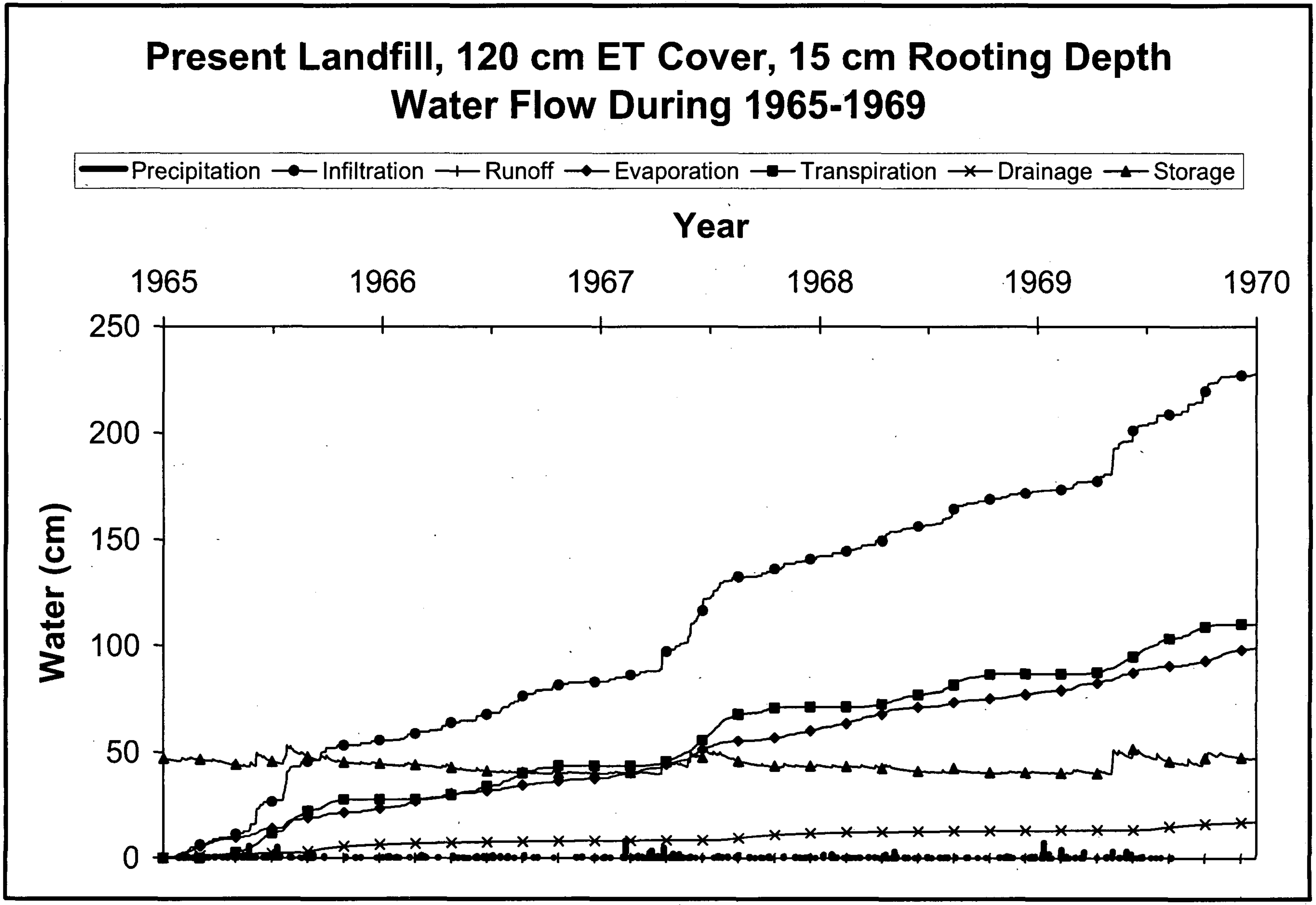

Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
Water (cm)
250
200
150
100
50
0

Figure A1-58

103

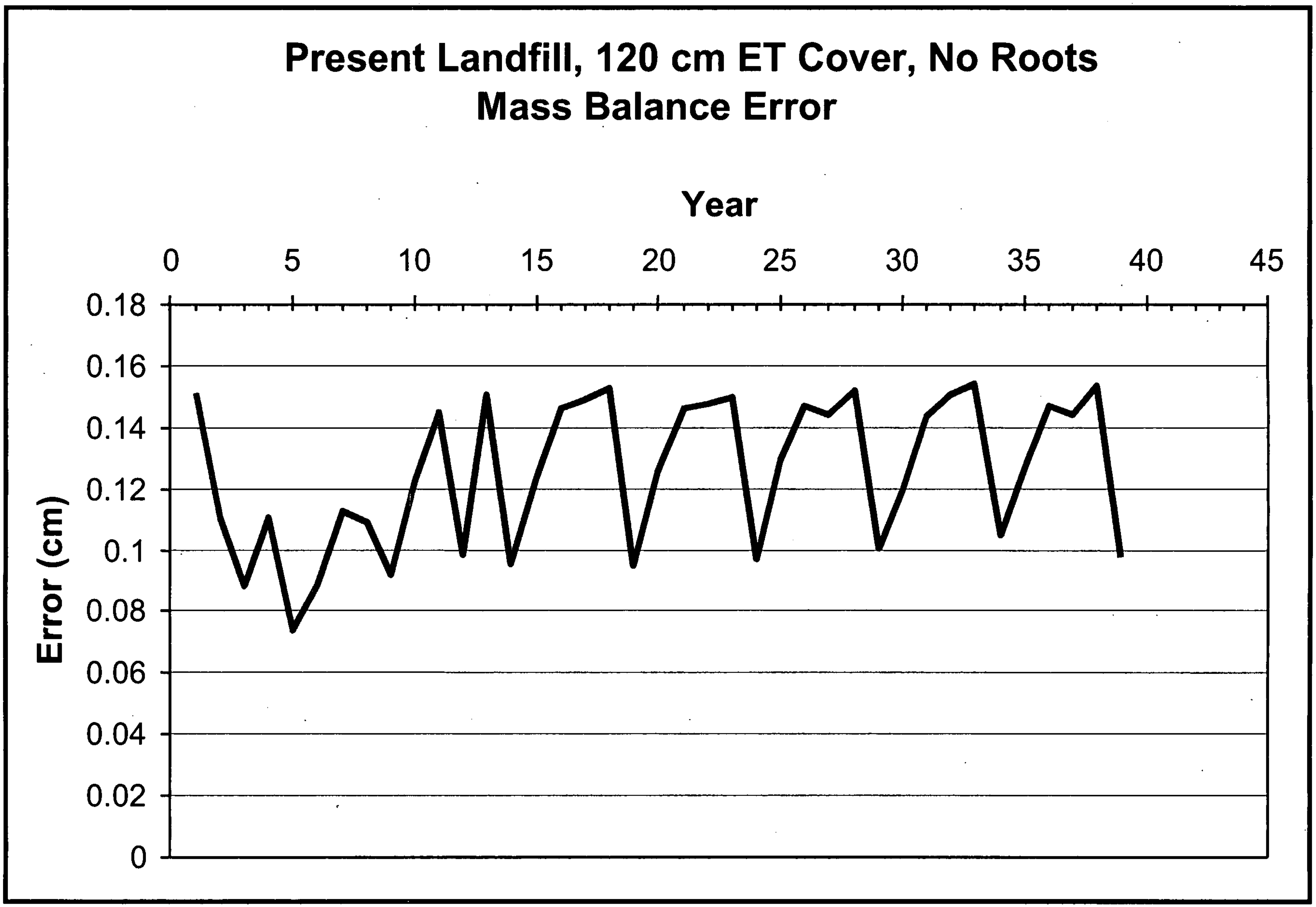
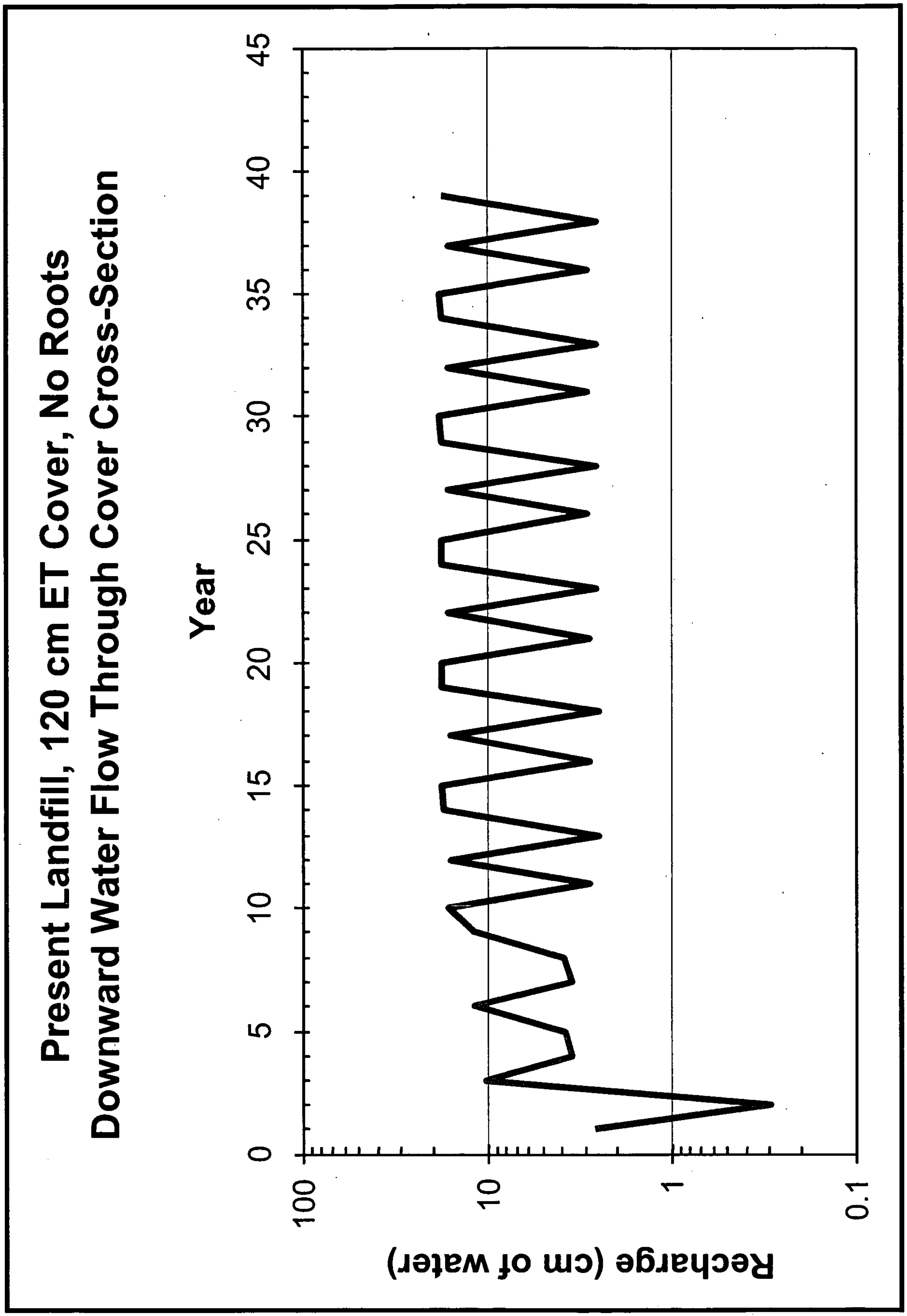


Figure A1-59



Present Landfill, 120 cm ET Cover, No Roots
Downward Water Flow Through Cover Cross-Section
Year
0
5
10
15
20
25
30
35
40
45
Recharge (cm of water)
100
10
1
0.1

Figure A1-60

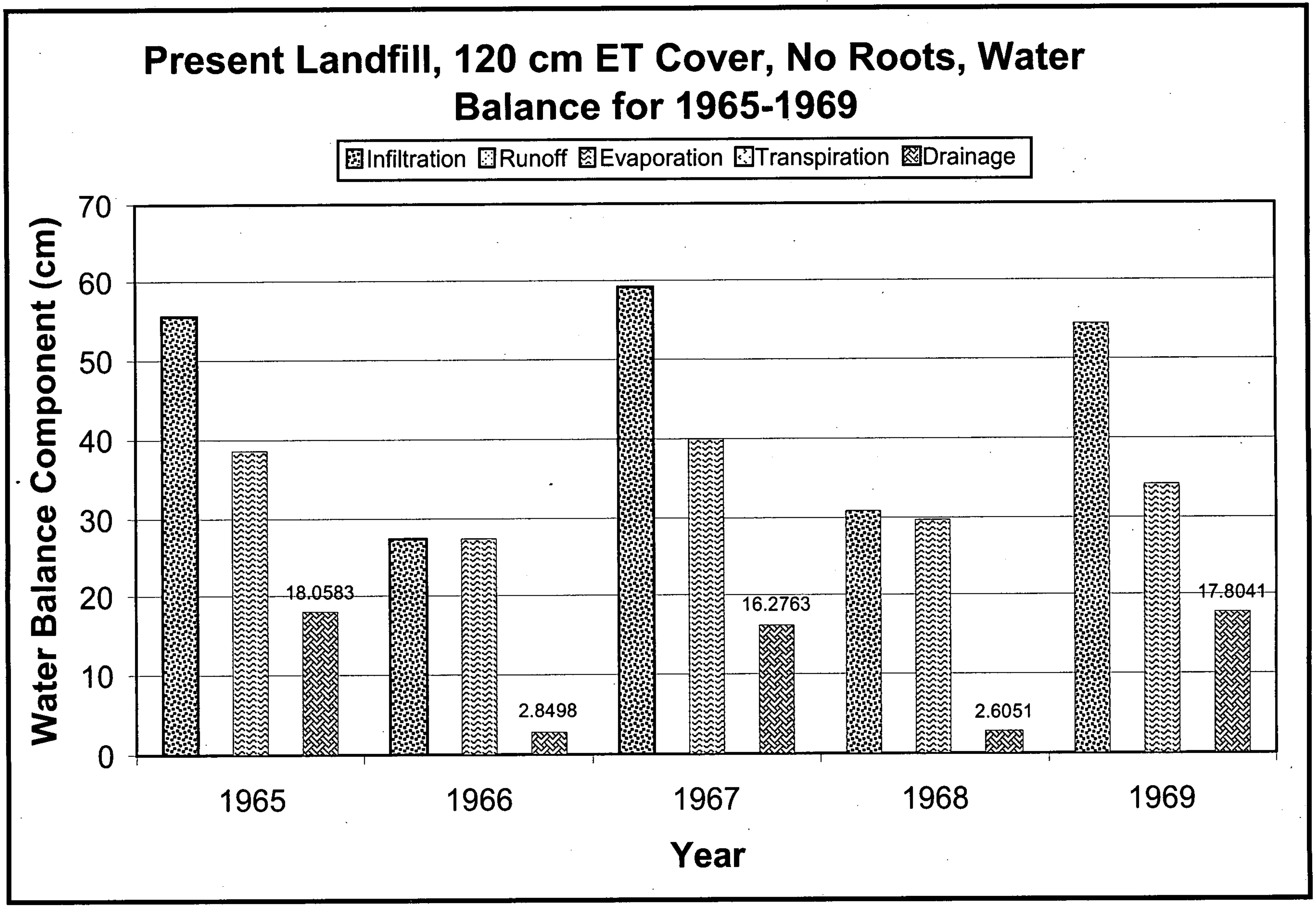


Figure A1-61

105

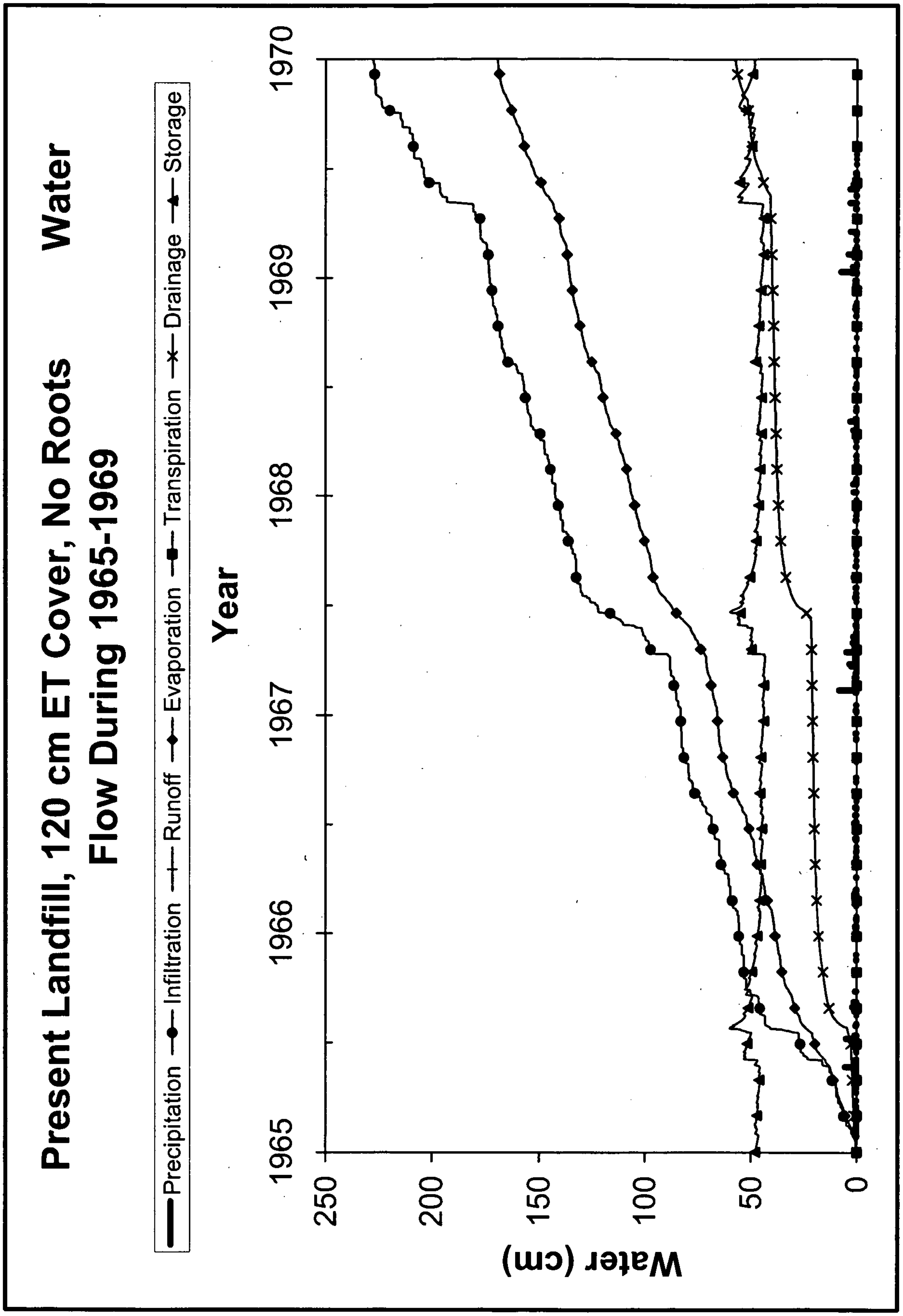


Figure A1-62

106

107

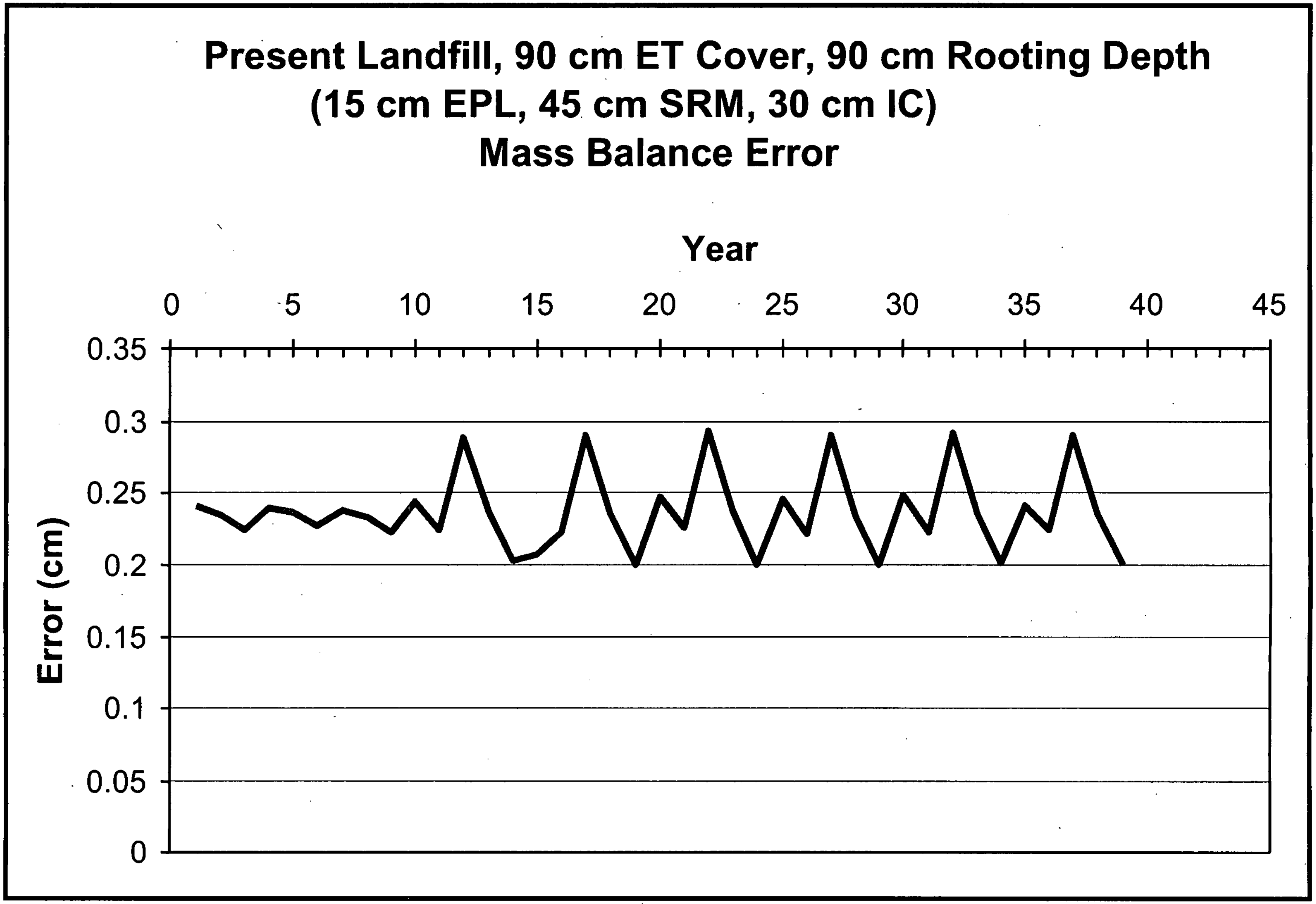


Figure A1-63

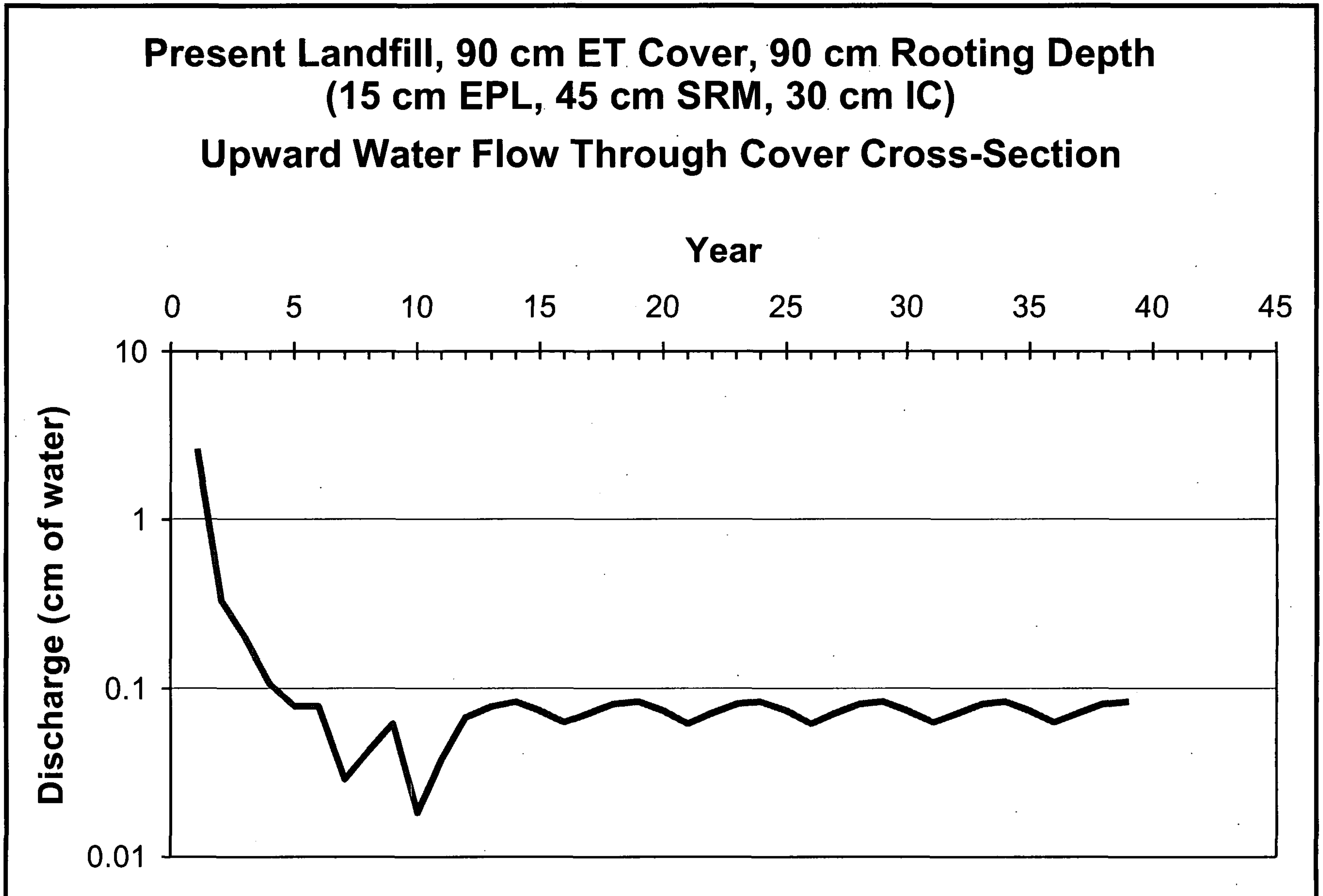
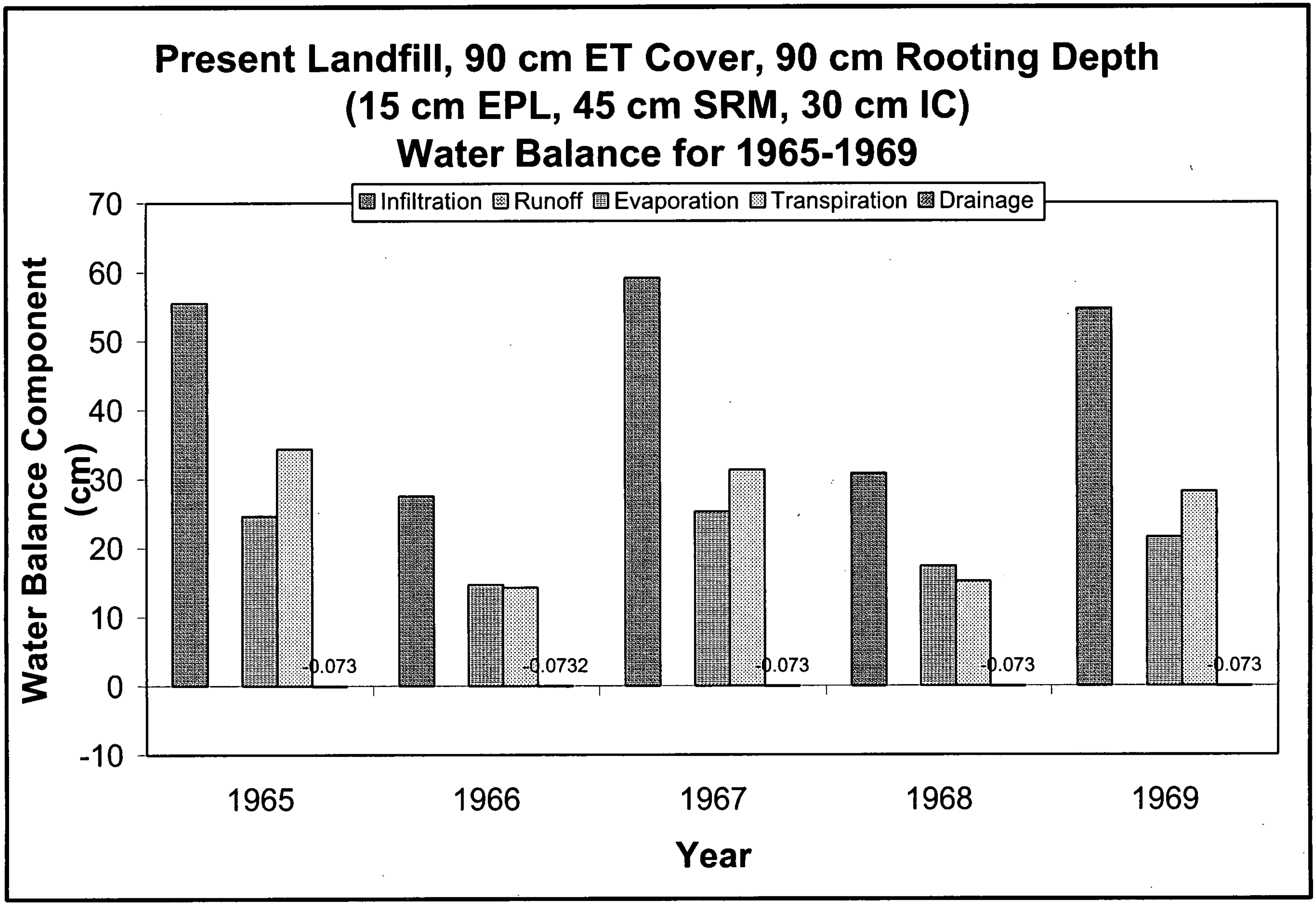


Figure A1-64

108



Present Landfill, 90 cm ET Cover, 90 cm Rooting Depth
(15 cm EPL, 45 cm SRM, 30 cm IC)
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
-10
-0.073
-0.0732
-0.073
-0.073
-0.073
1965
1966
1967
1968
1969
Year

Figure A1-65

Present Landfill, 90 cm ET Cover, 90 cm Rooting Depth (15 cm EPL, 45 cm SRM, 30 cm IC) Water Flow During 1965-1969

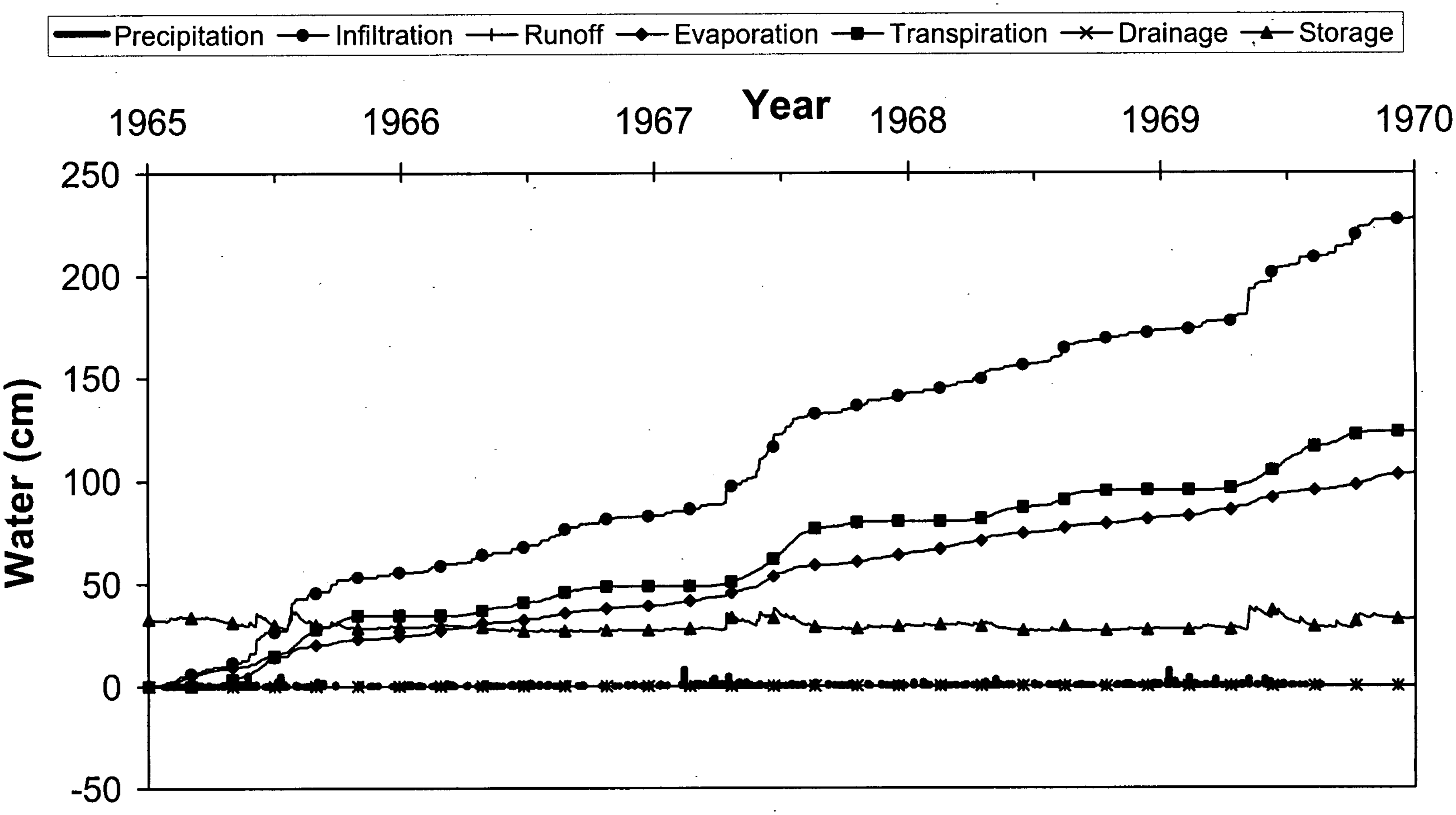


Figure A1-66

Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth (30 cm EPL, 30 cm SRM, 15 cm Venting Layer) Mass Balance Error

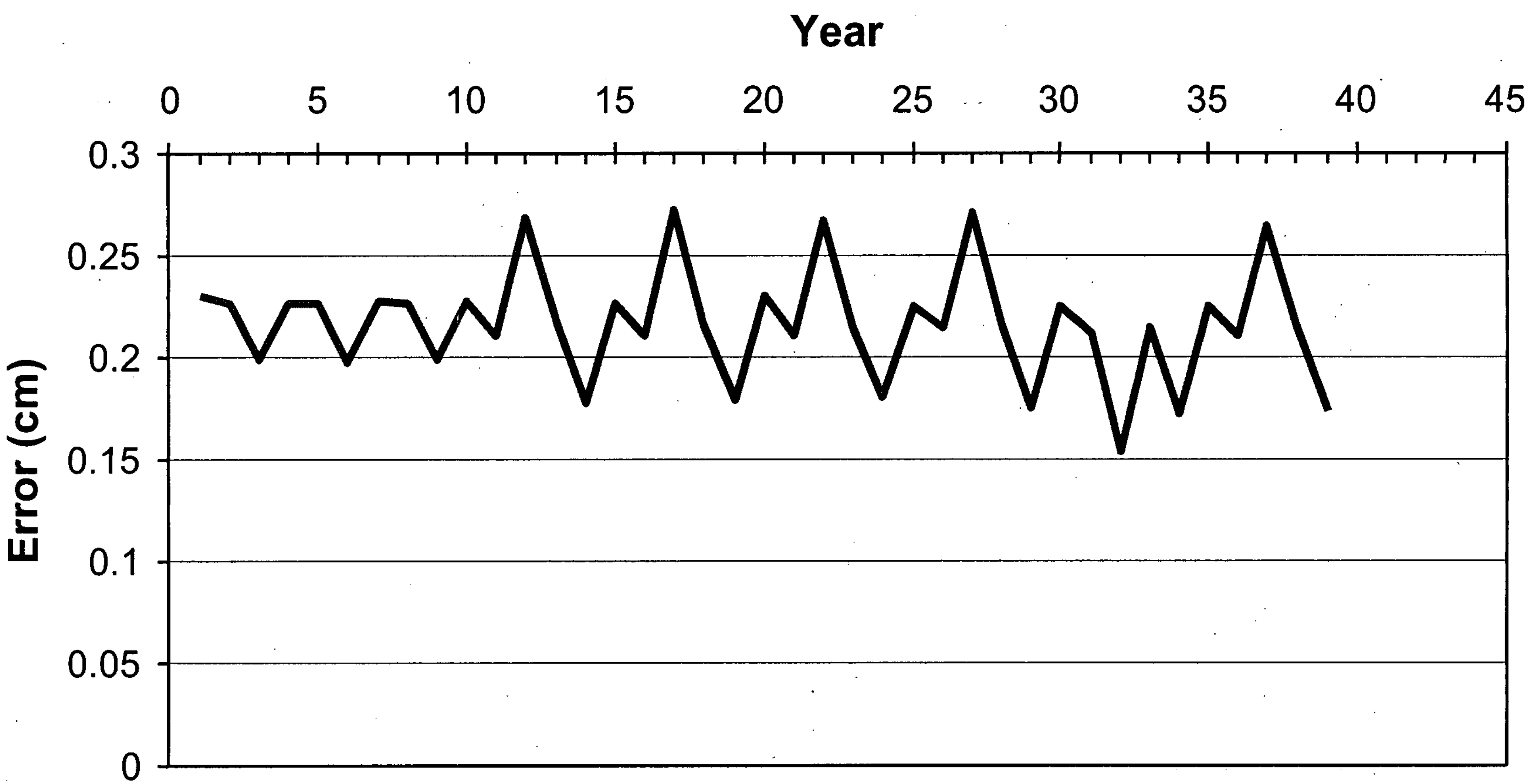


Figure A1-67

Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth
(30 cm EPL, 30 cm SRM, 15 cm Venting Layer)
Downward Water Flow Through Cover Cross-Section

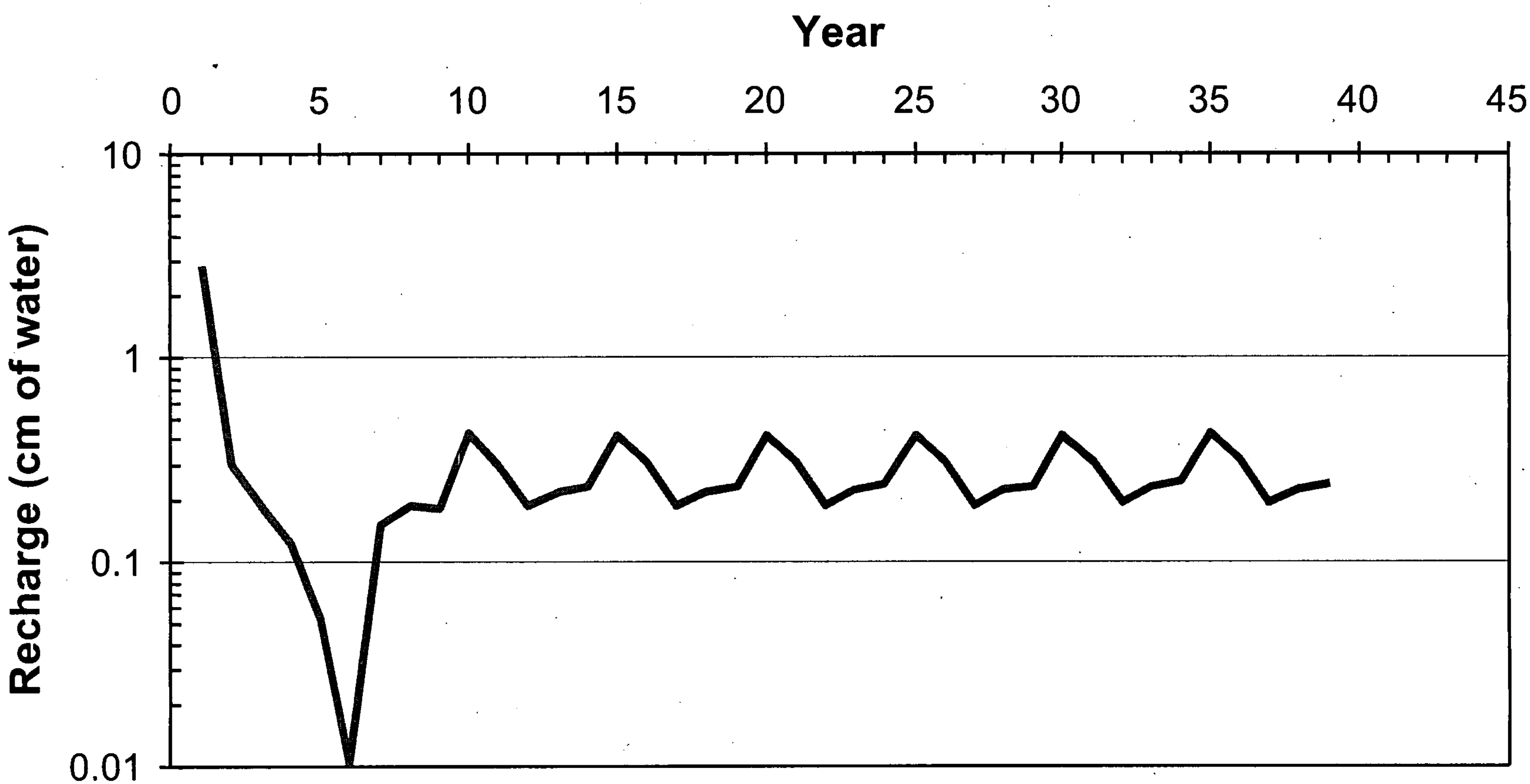
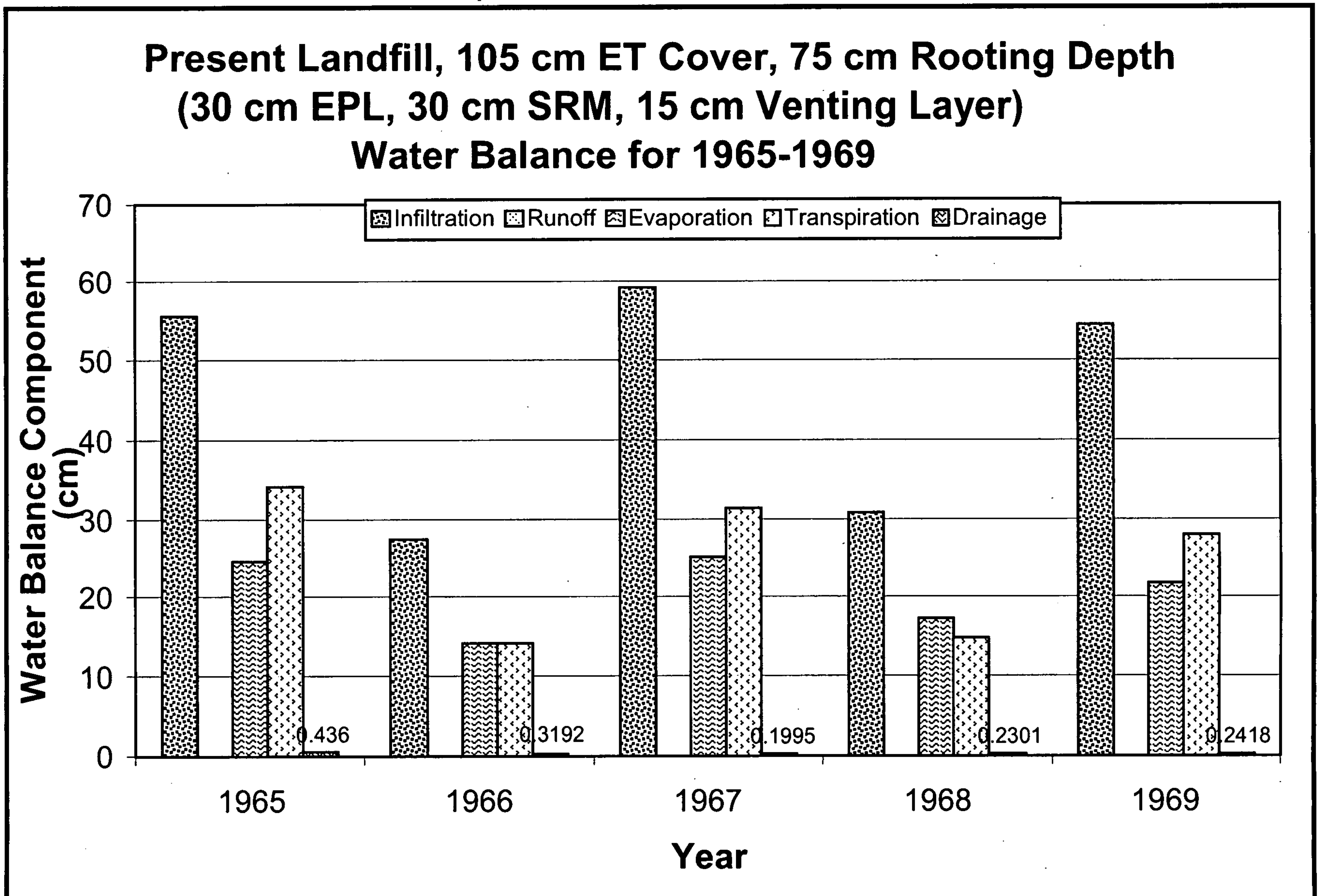


Figure A1-68



Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth
(30 cm EPL, 30 cm SRM, 15 cm Venting Layer)
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
0.436
0.3192
0.1995
0.2301
0.2418
1965
1966
1967
1968
1969
Year

Figure A1-69

114

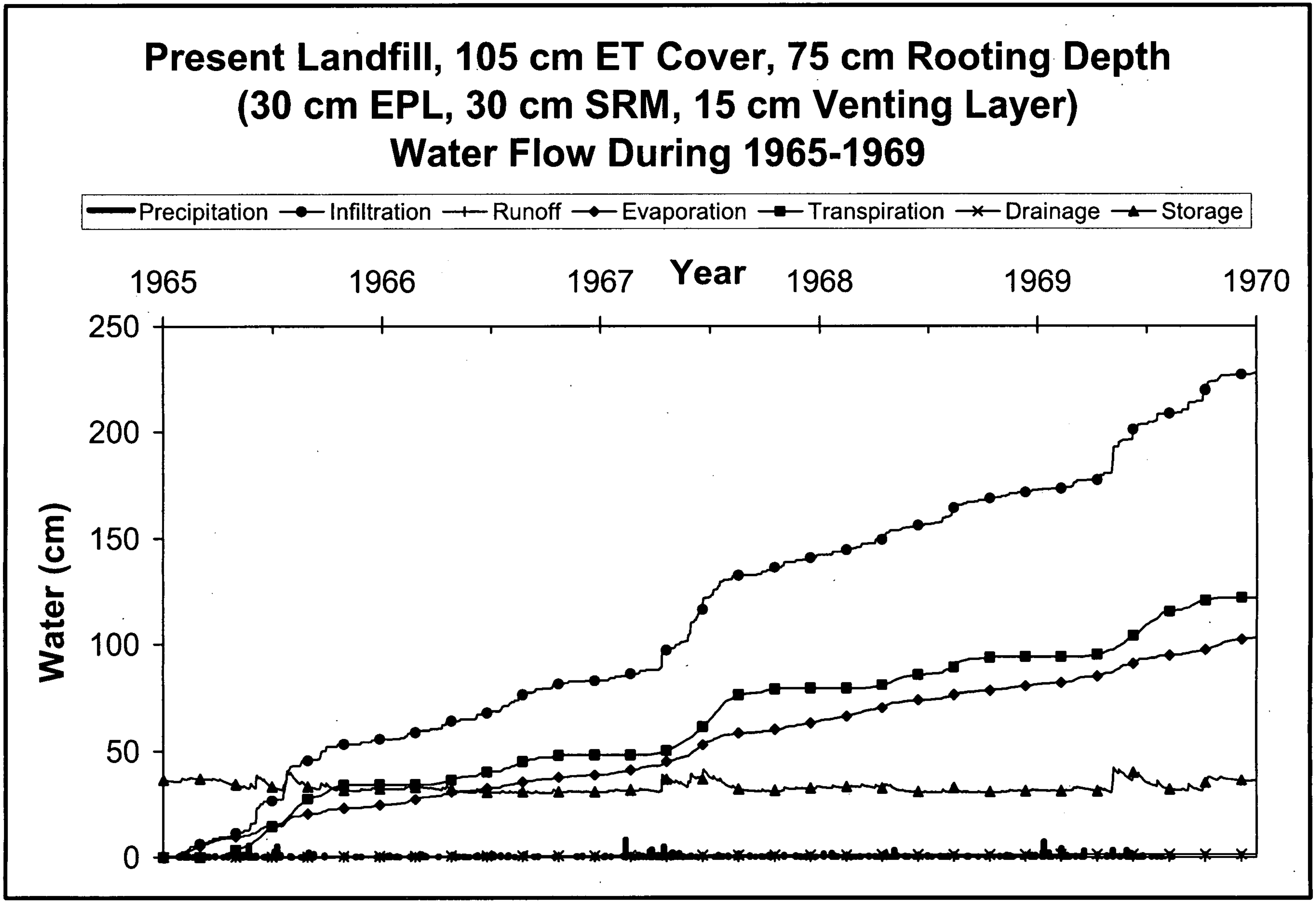


Figure A1-70

105

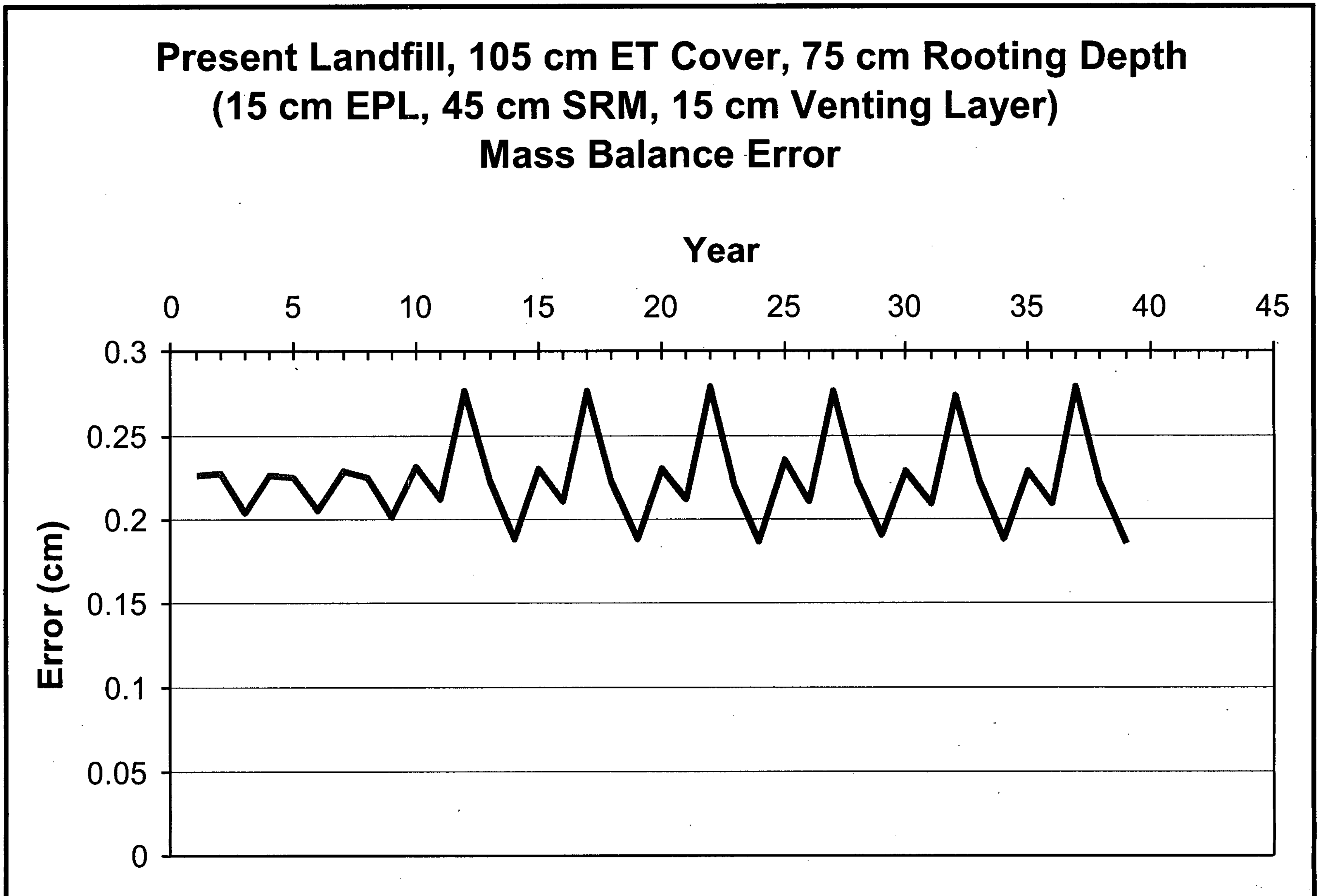


Figure A1-71

Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth
(15 cm EPL, 45 cm SRM, 15 cm Venting Layer)
Downward Water flow Through cover Cross-Section

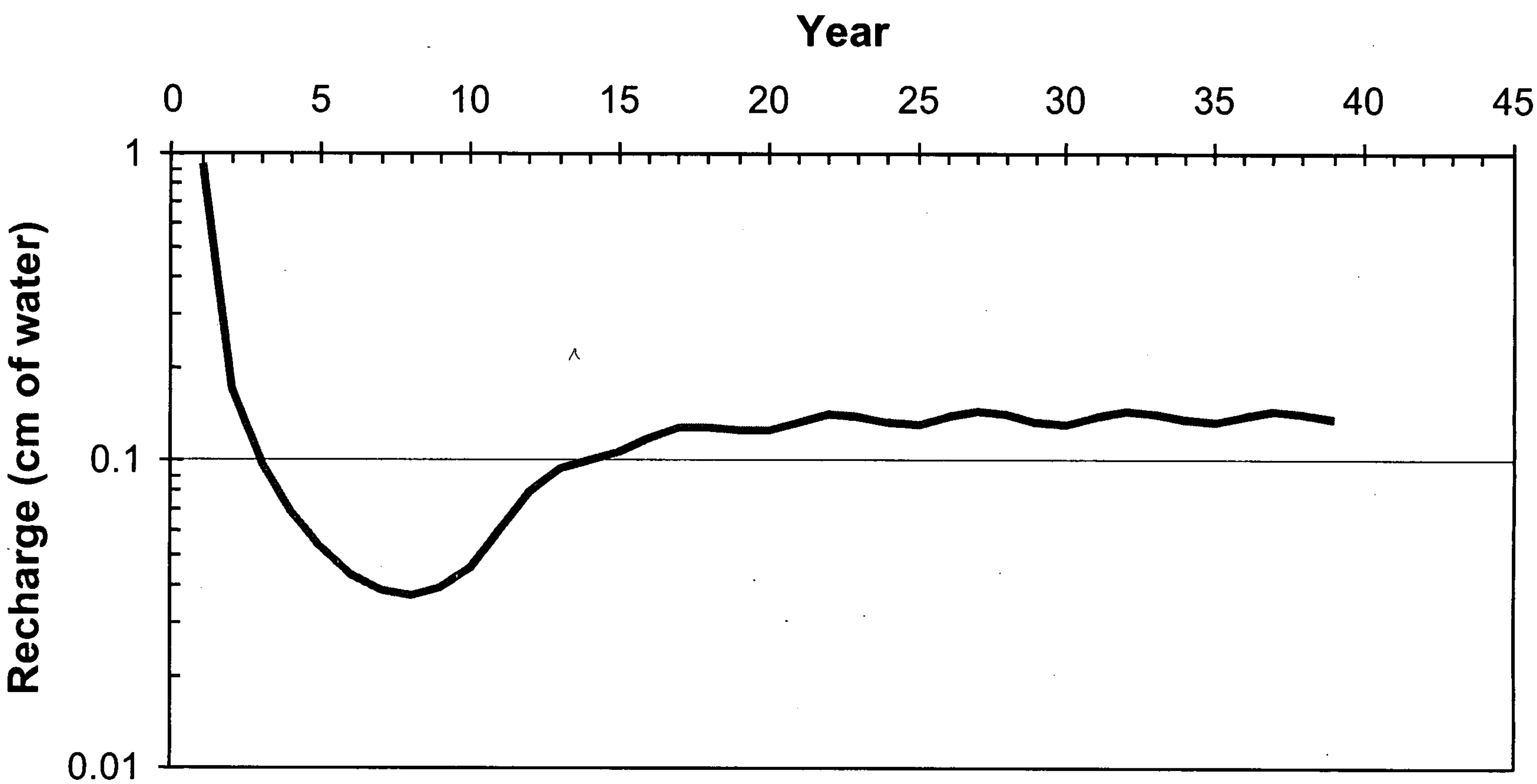


Figure A1-72

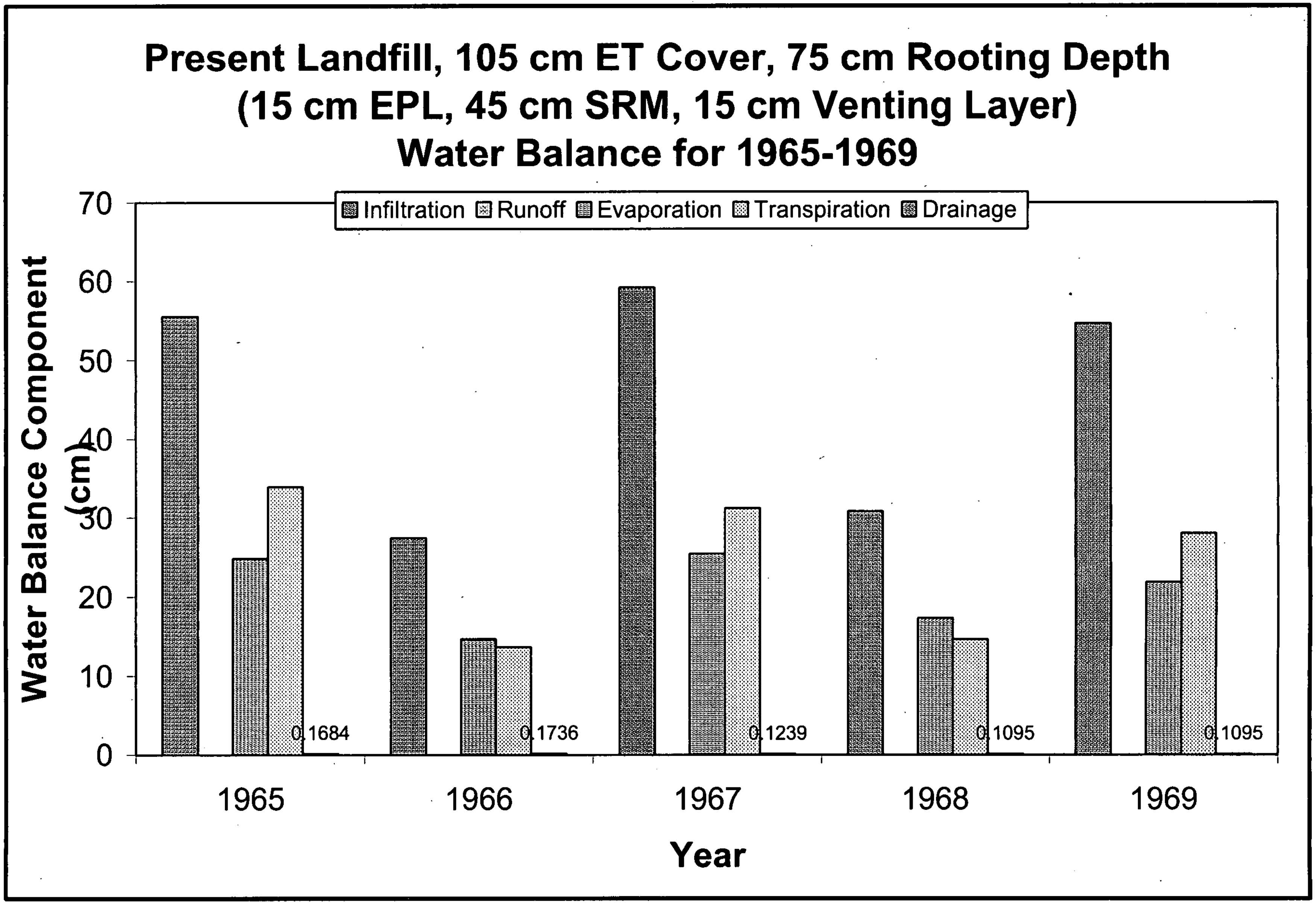

Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth
(15 cm EPL, 45 cm SRM, 15 cm Venting Layer)
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
0
10
20
30
40
50
60
70
0.1684
0.1736
0.1239
0.1095
0.1095
1965
1966
1967
1968
1969
Year

Figure A1-73

118

Present Landfill, 105 cm ET Cover, 75 cm Rooting Depth (15 cm EPL, 45 cm SRM, 15 cm Venting Layer) Water Flow During 1965-1969

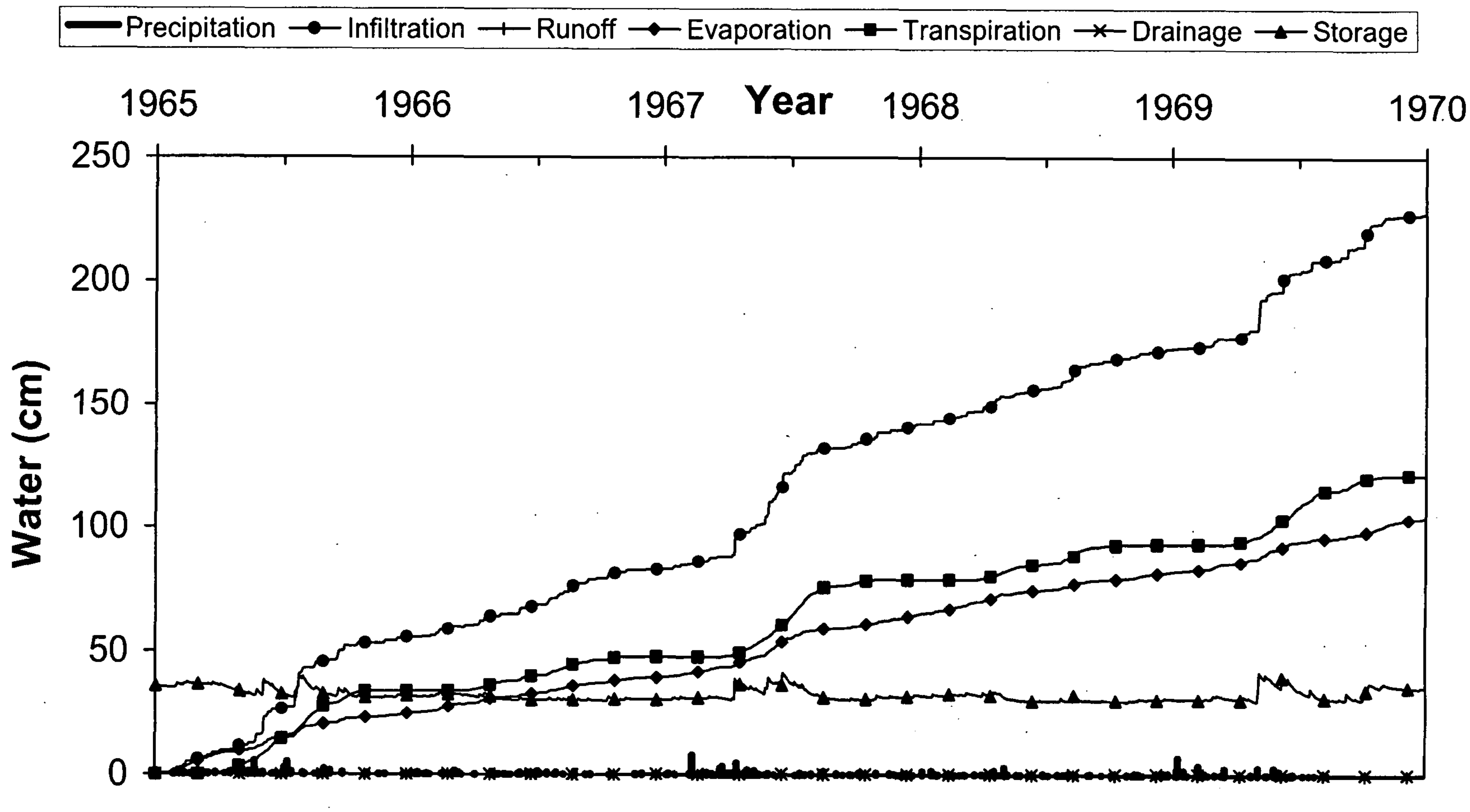


Figure A1-74

/19

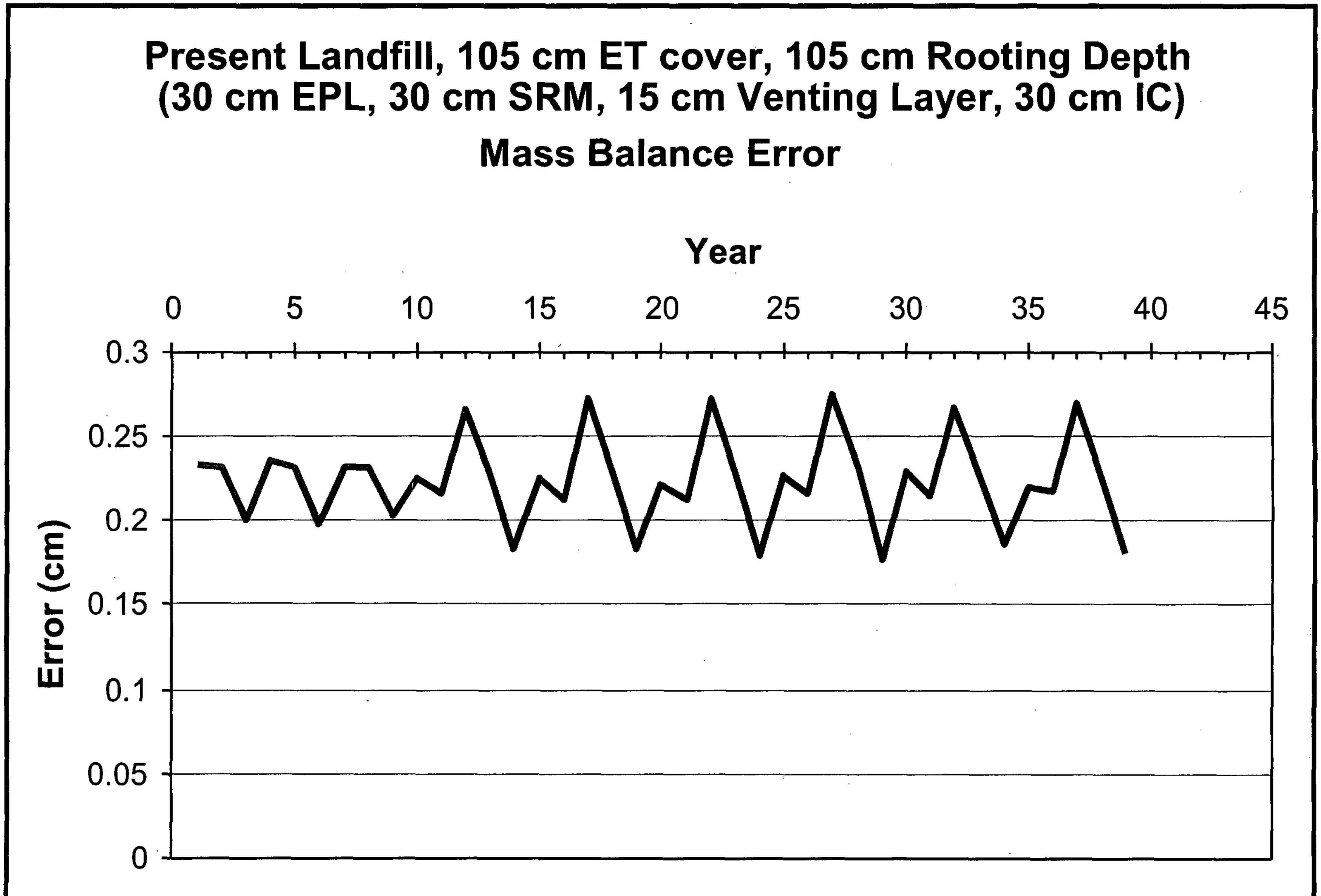


Figure A1-75

120

Present Landfill, 105 cm ET cover, 105 cm Rooting Depth (30 cm EPL, 30 cm SRM, 15 cm Venting Layer, 30 cm IC)

Upward Water Flow Through Cover Cross-Section

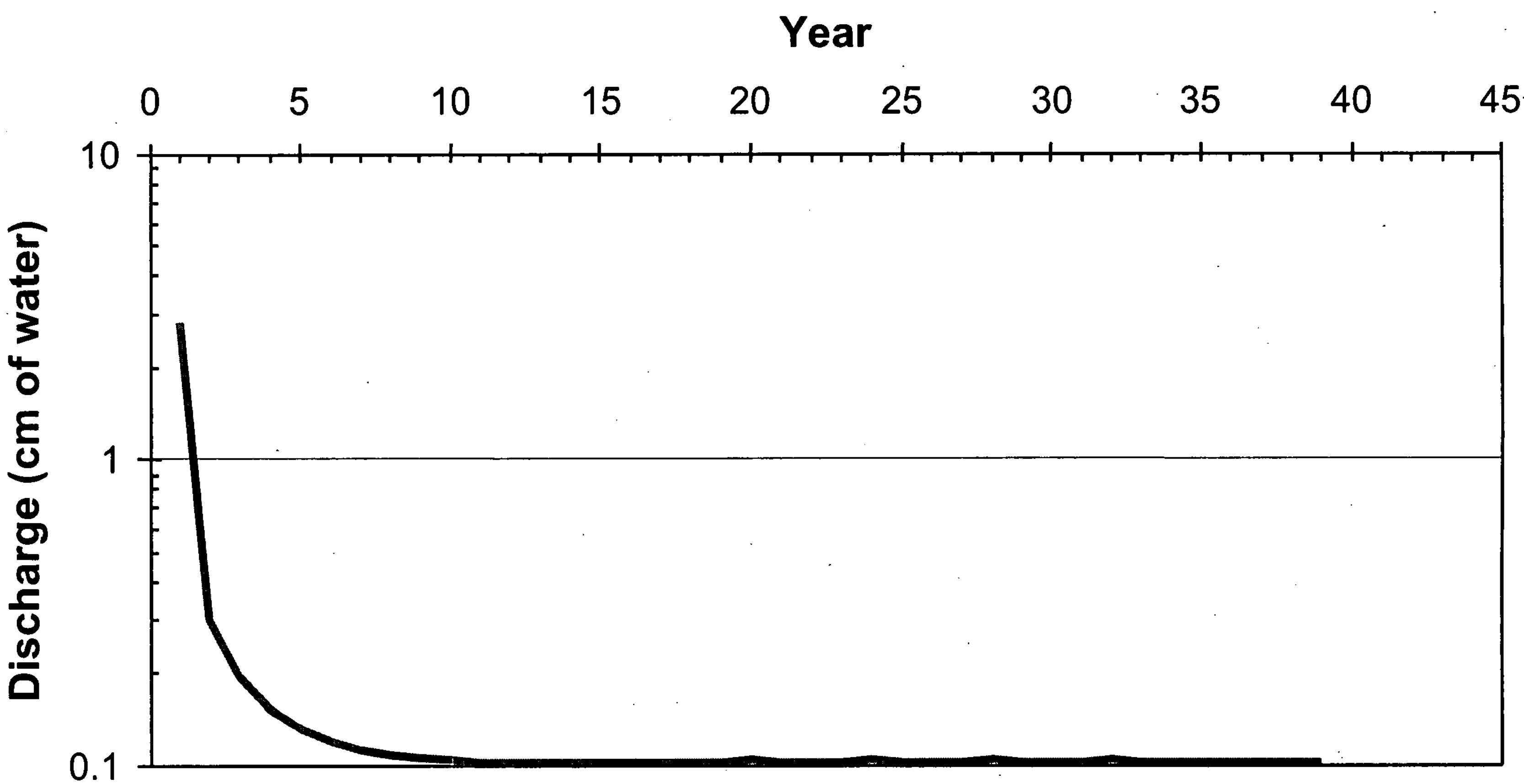


Figure A1-76

121

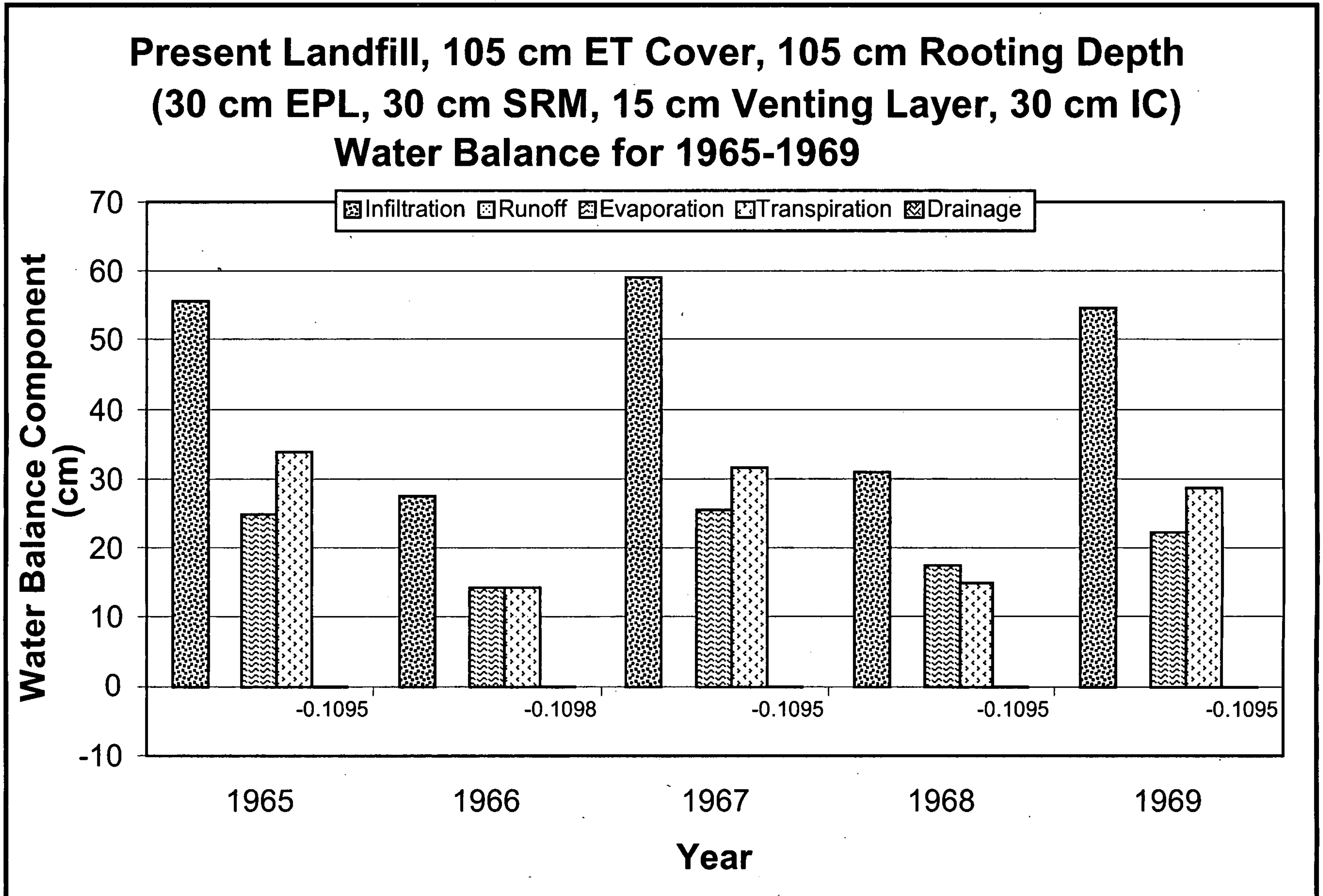
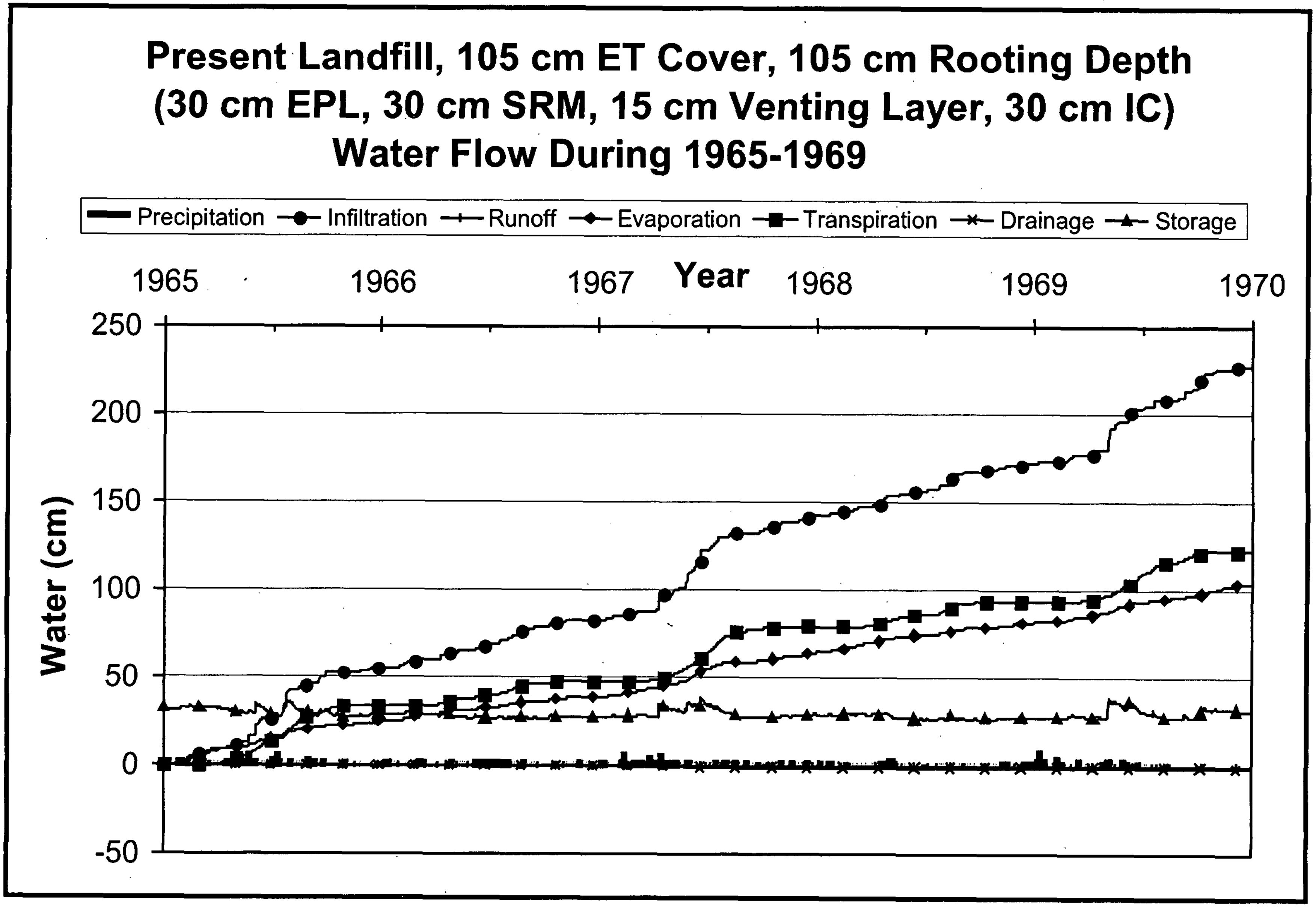


Figure A1-77



Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
(30 cm EPL, 30 cm SRM, 15 cm Venting Layer, 30 cm IC)
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
Water (cm)
250
200
150
100
50
0
-50

Figure A1-78

123

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth
(15 cm EPL, 45 cm SRM, 15 cm Venting Layer, 30 cm IC)
Mass Balance Error

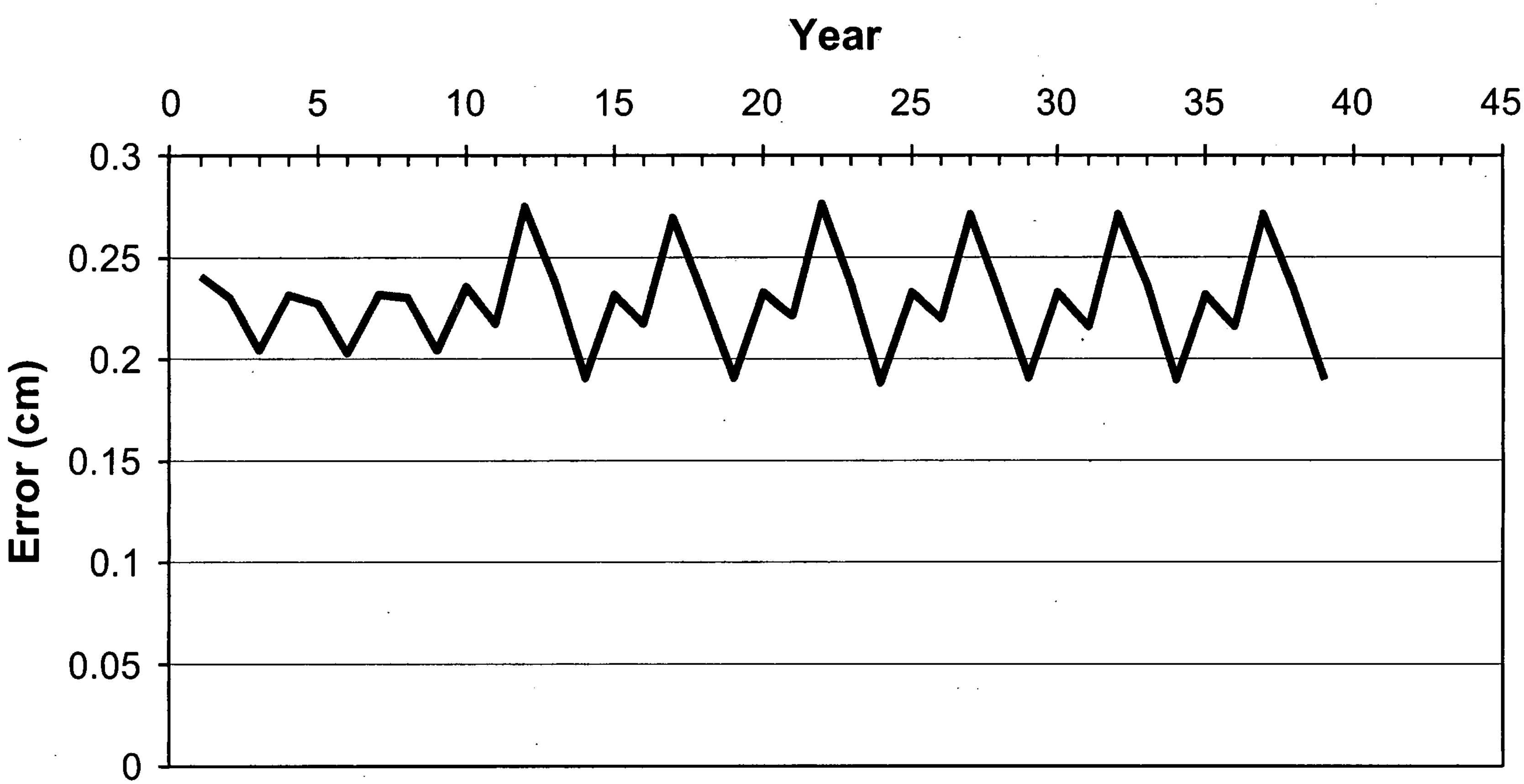


Figure A1-79

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth (15 cm EPL, 45 cm SRM, 15 cm Venting Layer, 30 cm IC) Upward Water Flow Through Cover Cross-Section

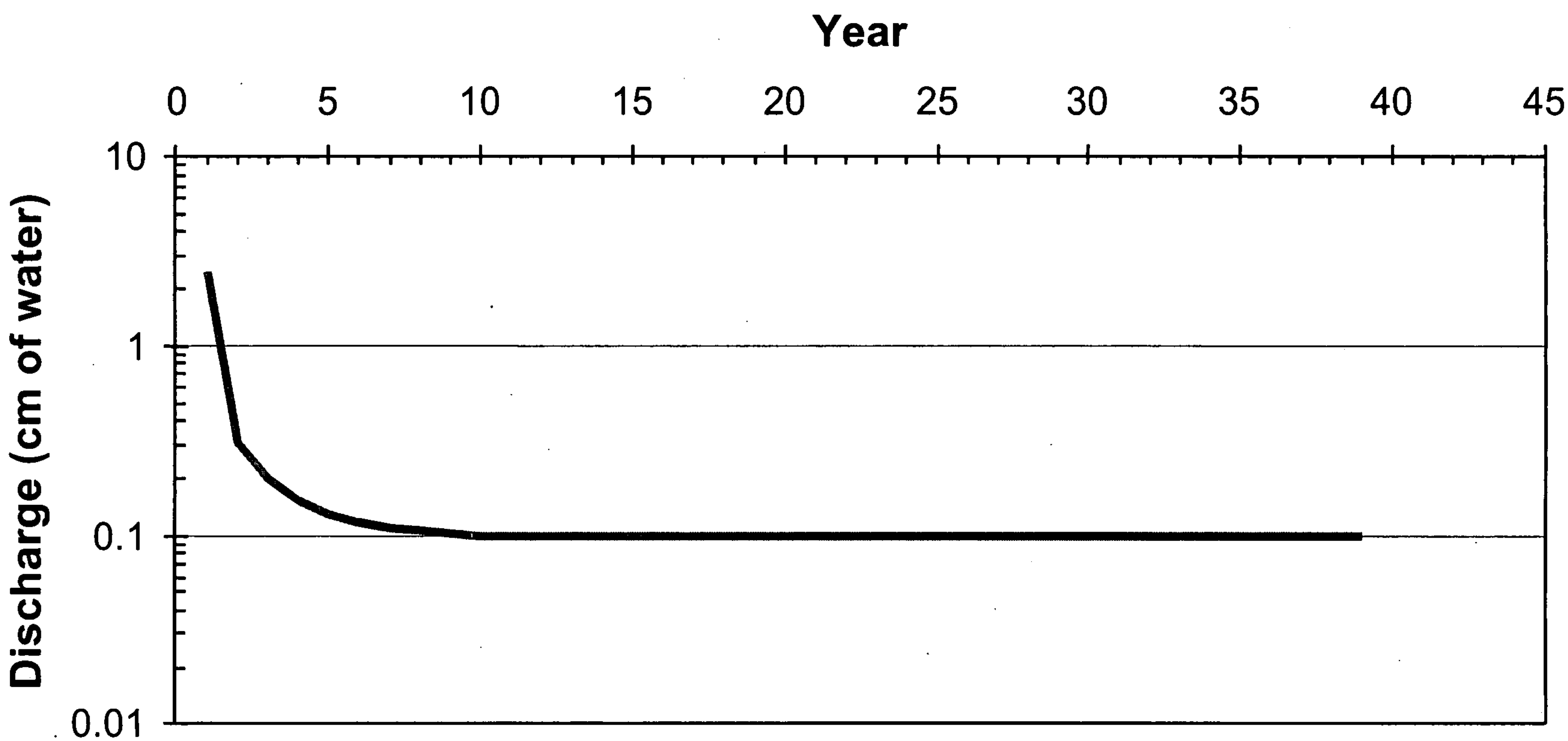


Figure A1-80

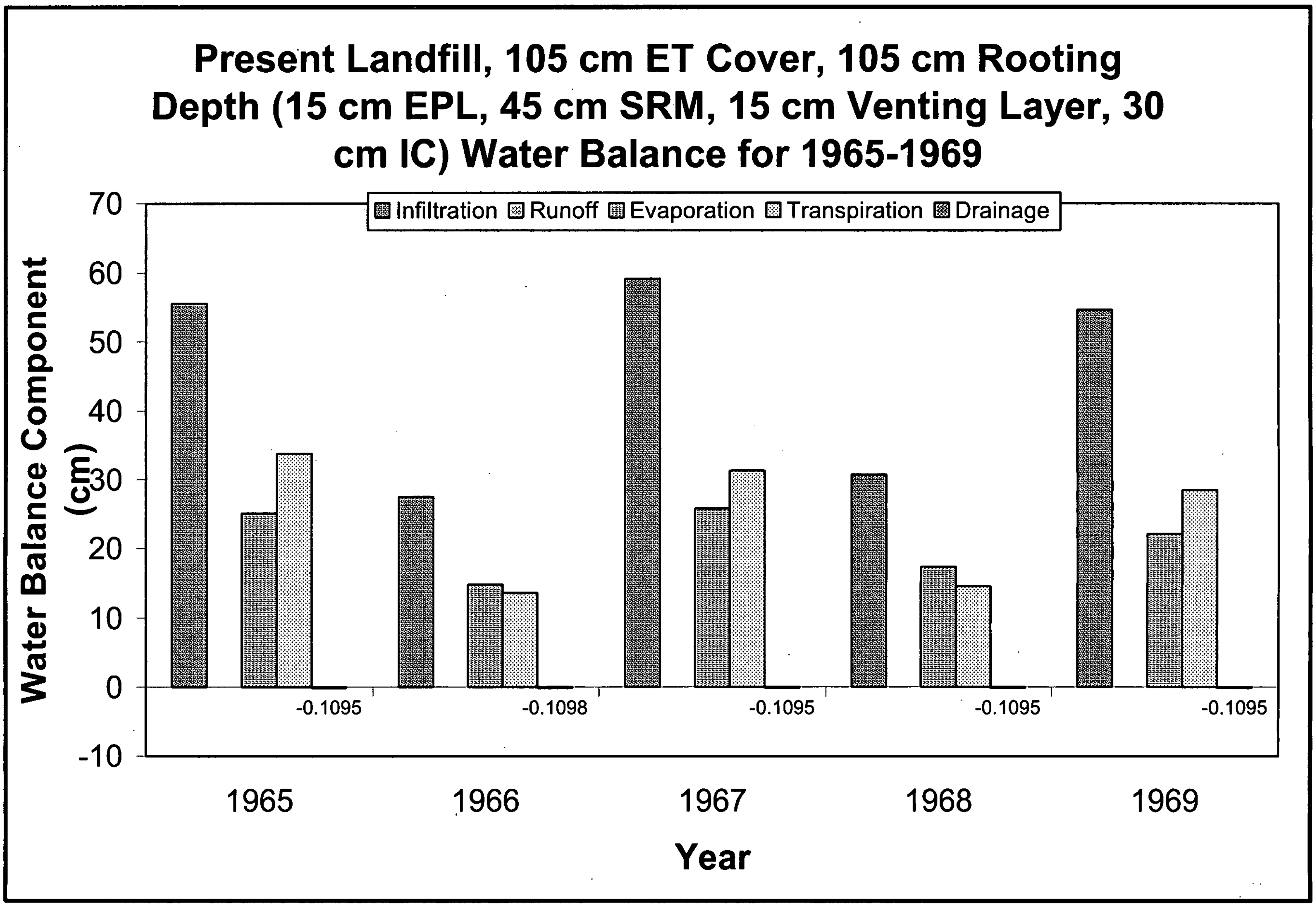

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth (15 cm EPL, 45 cm SRM, 15 cm Venting Layer, 30 cm IC) Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
70
60
50
40
30
20
10
0
-10
-0.1095
-0.1098
-0.1095
-0.1095
-0.1095
1965
1966
1967
1968
1969
Year

Figure A1-81

Present Landfill, 105 cm ET Cover, 105 cm Rooting Depth (15 cm EPL, 45 cm SRM, 15 cm Venting Layer, 30 cm IC) Water Flow During 1965-1969

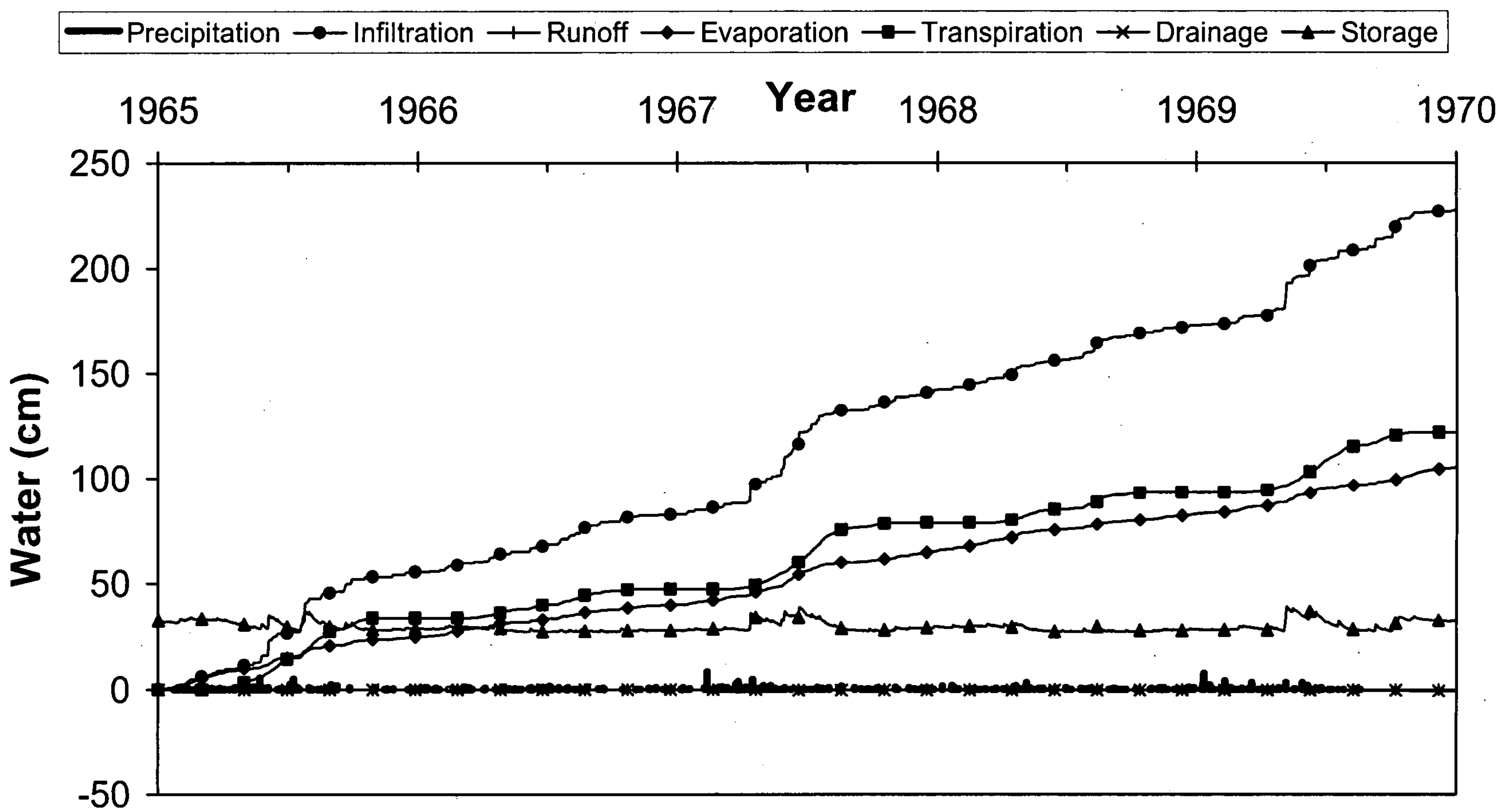


Figure A1-82

127

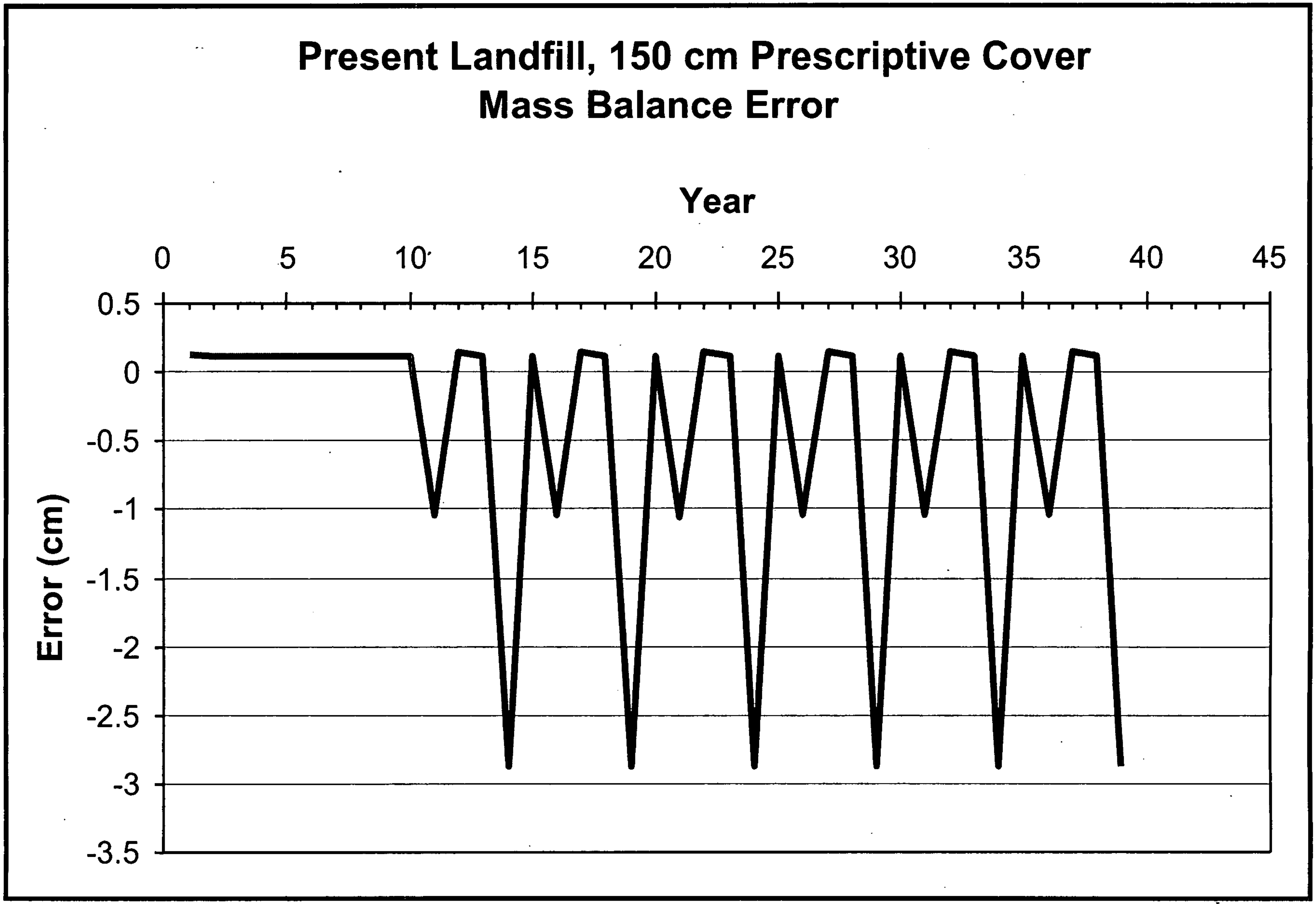


Figure A1-83

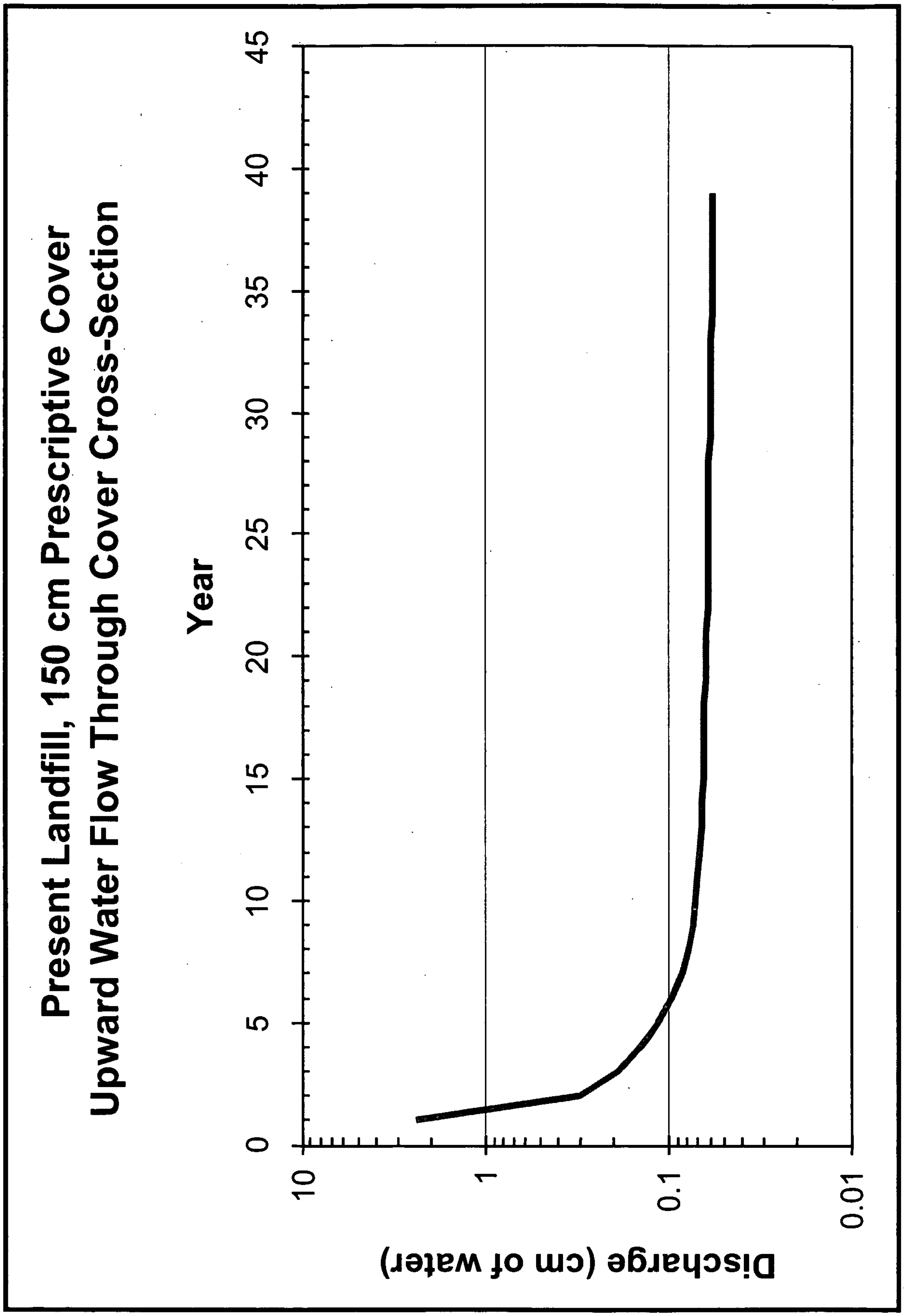


Figure A1-84

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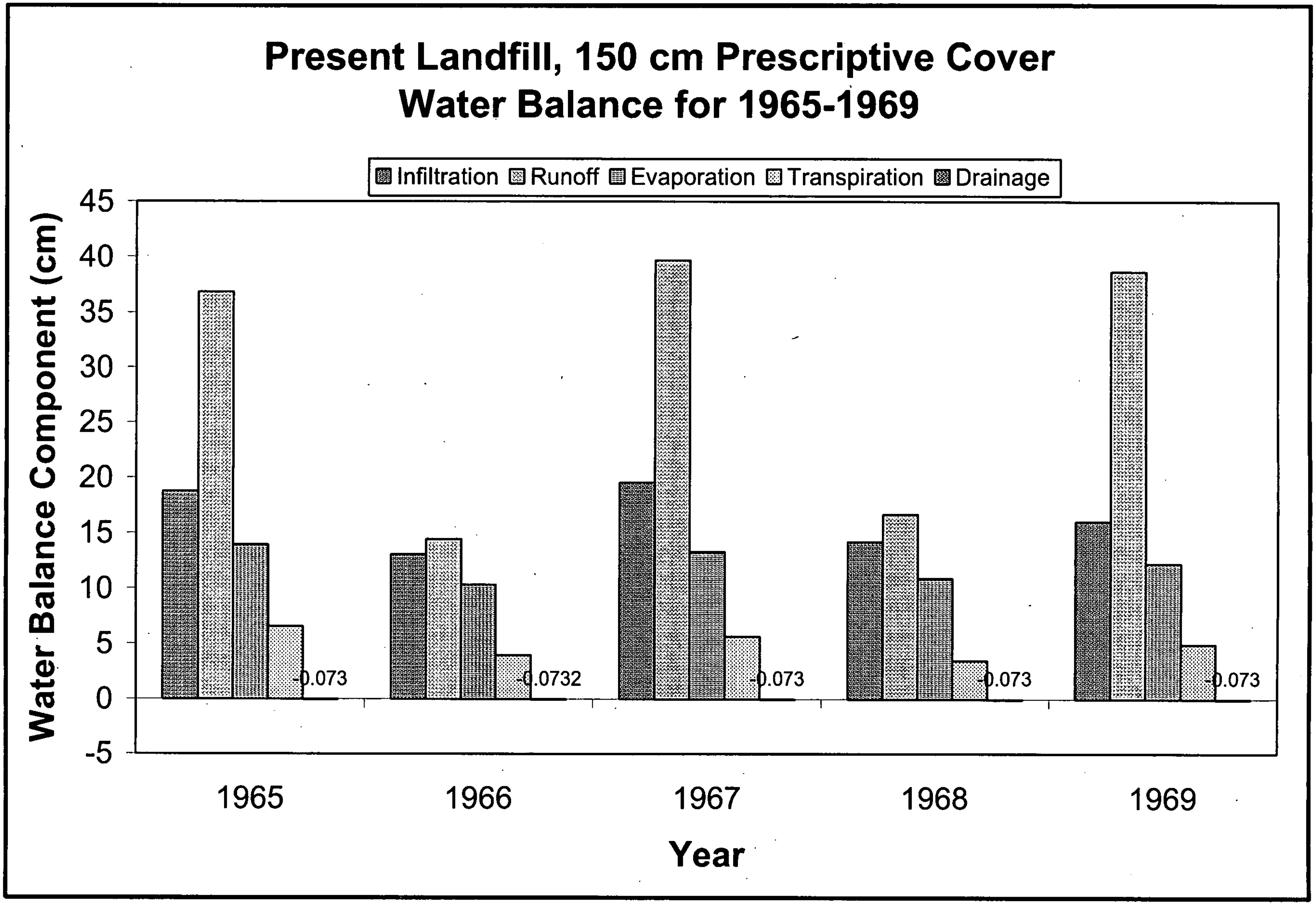

Figure A1-85

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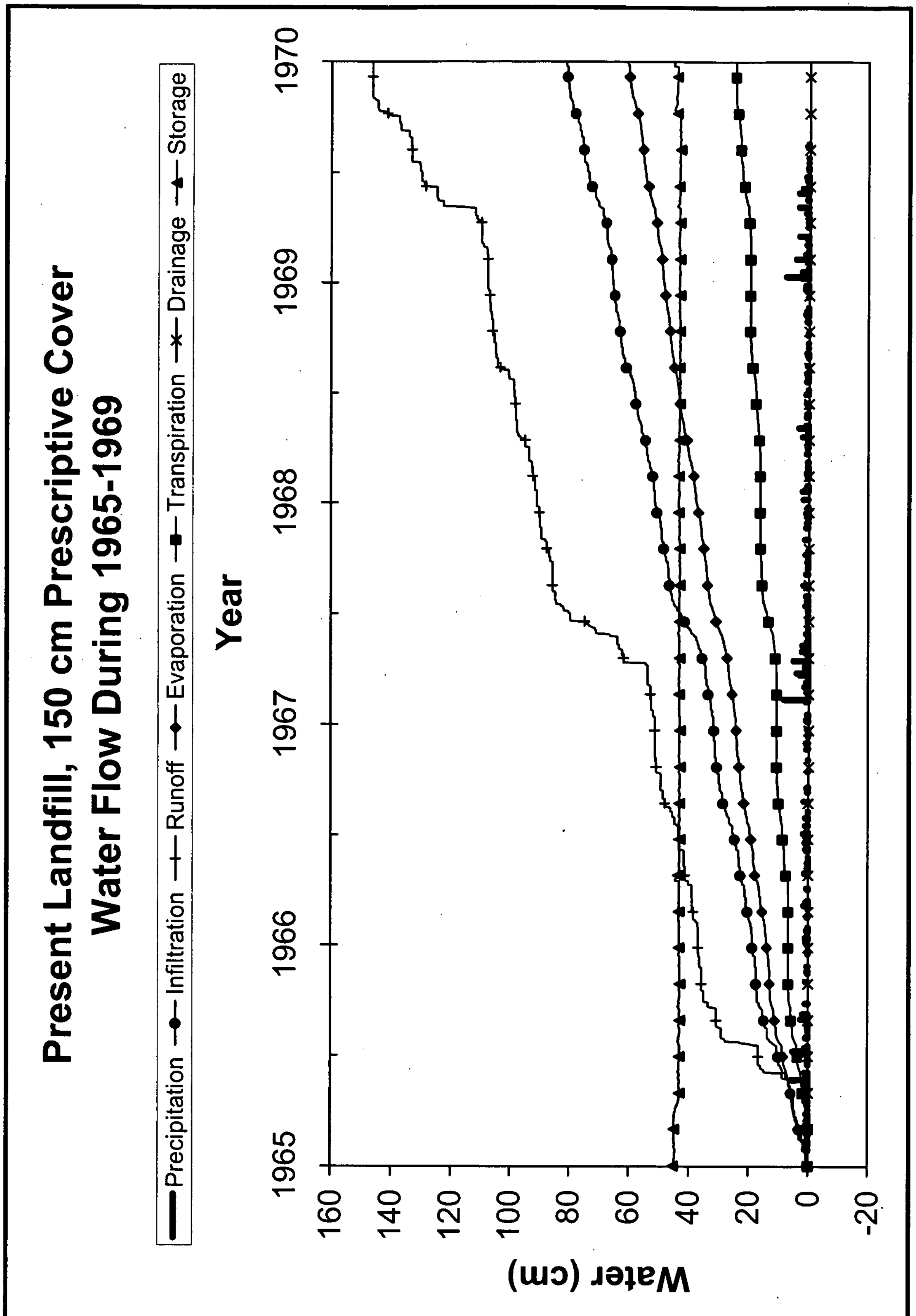


Figure A1-86

130

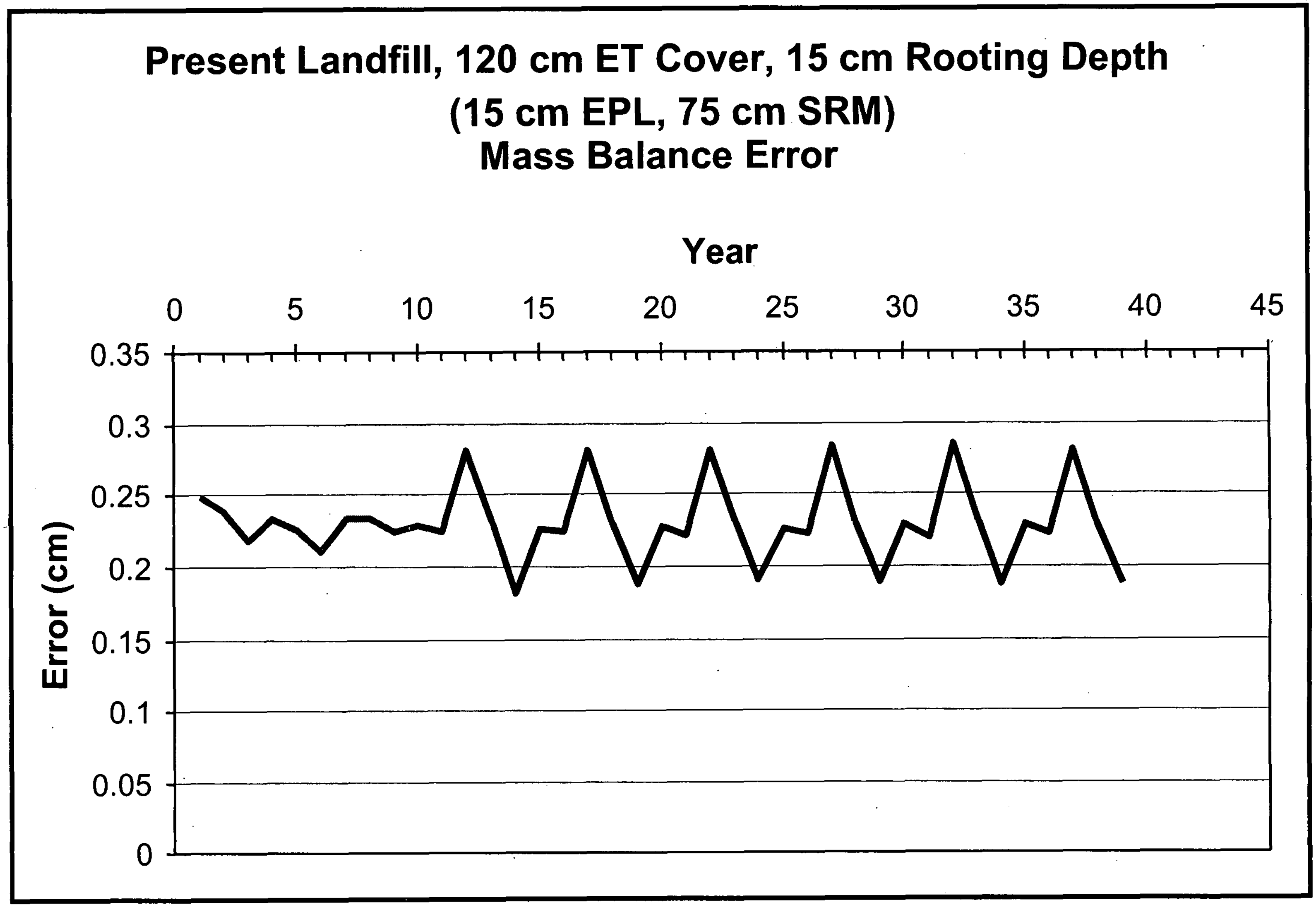

Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
(15 cm EPL, 75 cm SRM)
Mass Balance Error
Year
0
5
10
15
20
25
30
35
40
45
Error (cm)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure A1-87

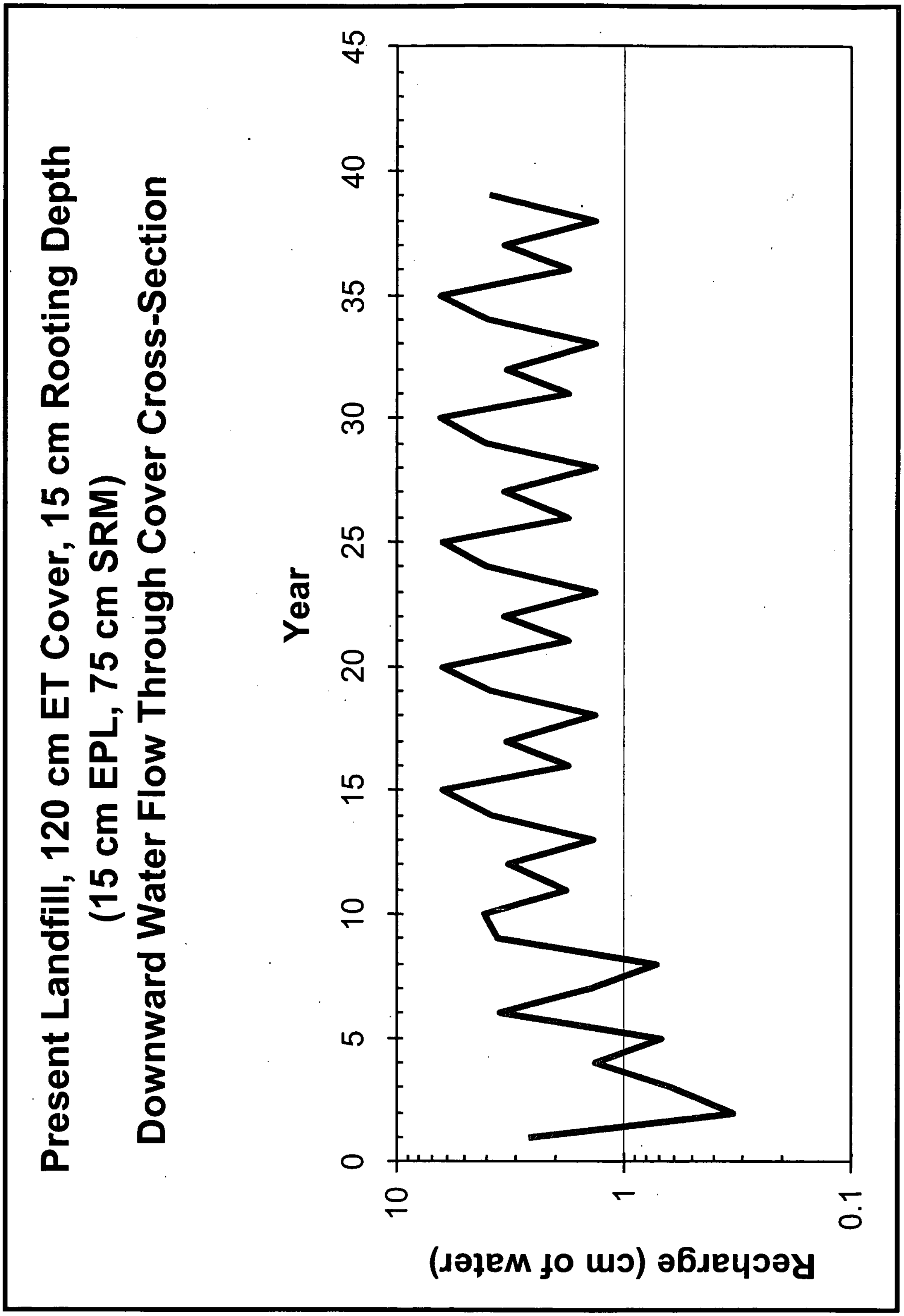


Figure A1-88

132

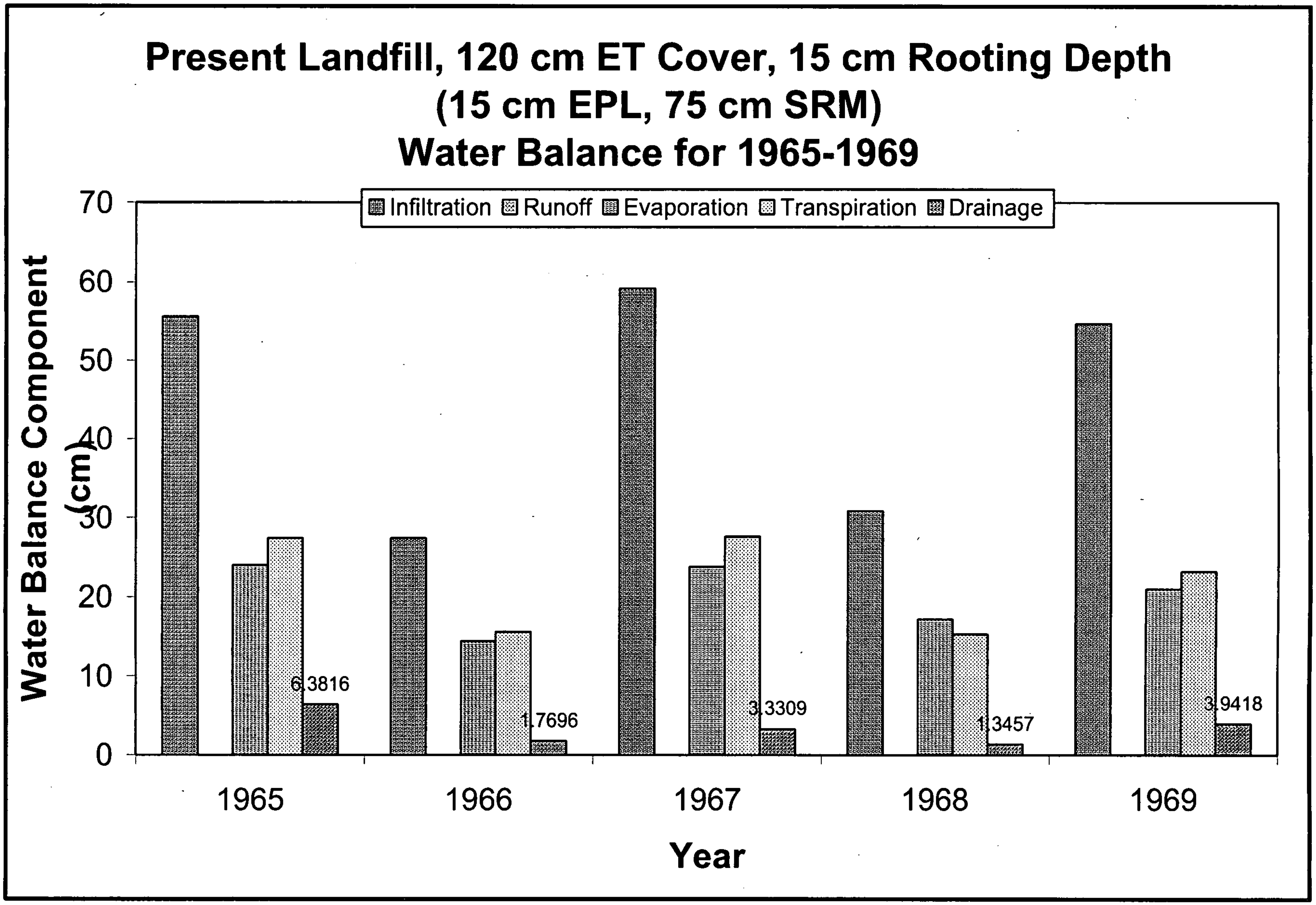
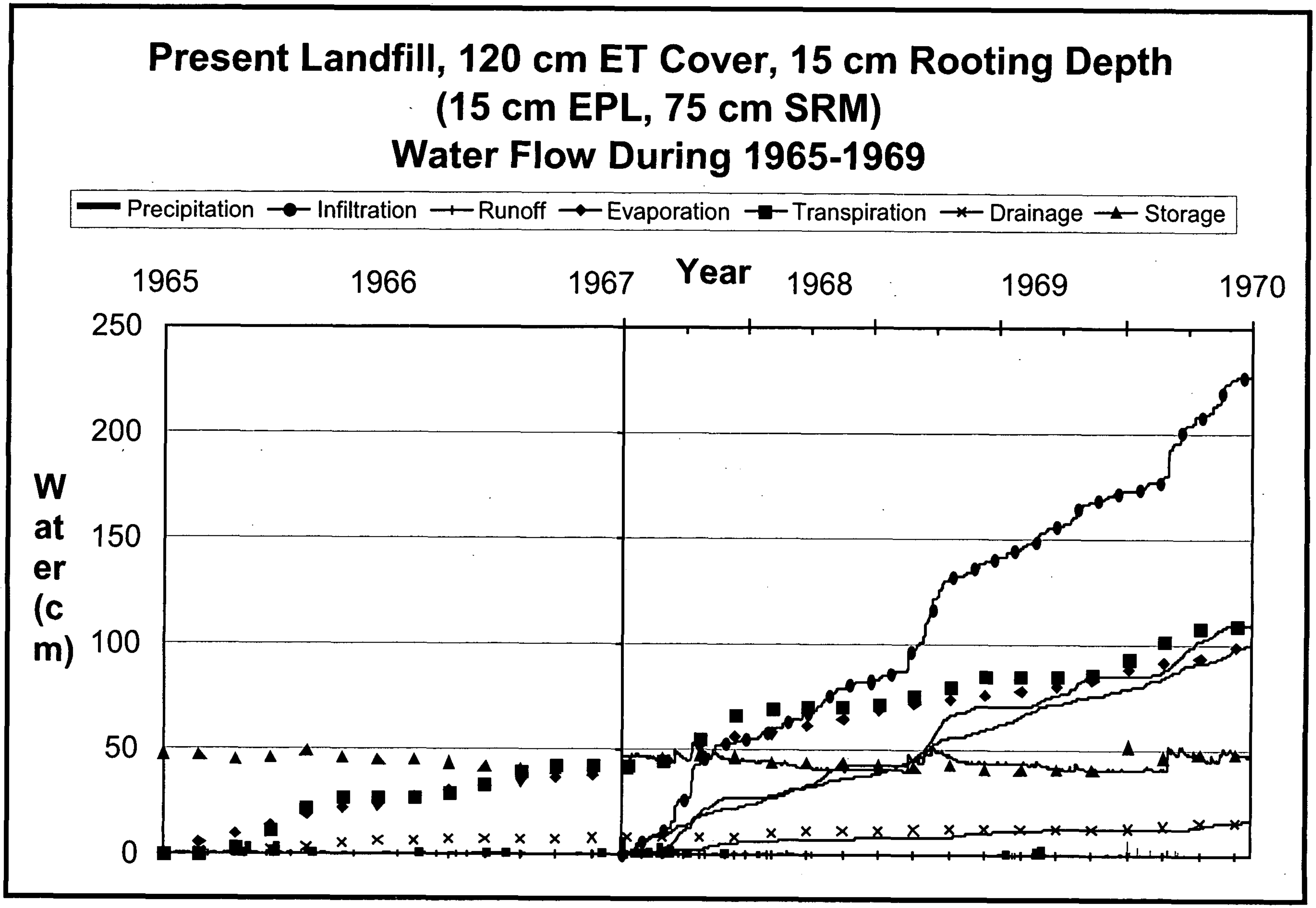

Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
(15 cm EPL, 75 cm SRM)
Water Balance for 1965-1969
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Water Balance Component (cm)
0
10
20
30
40
50
60
70
6.3816
1.7696
3.3309
1.3457
3.9418
1965
1966
1967
1968
1969
Year

Figure A1-89



Present Landfill, 120 cm ET Cover, 15 cm Rooting Depth
(15 cm EPL, 75 cm SRM)
Water Flow During 1965-1969
Precipitation
Infiltration
Runoff
Evaporation
Transpiration
Drainage
Storage
Year
1965
1966
1967
1968
1969
1970
Water (cm)
250
200
150
100
50
0

Figure A1-90

Appendix B

Feasibility Study

Feasibility Study of an Evapotranspiration Cover for the Present Landfill Rocky Flats Environmental Technology Site

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Appendix B. Feasibility Study of an Evapotranspiration Cover for the Present Landfill Rocky Flats Environmental Technology Site

B.1 Introduction

The purpose of the evapotranspiration (ET) cover modeling and conceptual design project is to develop a final cover design for the Present Landfill at the Rocky Flats Environmental Technology Site (RFETS). The design must consider local conditions and economic factors to facilitate final design and construction. The ET cover must achieve regulatory compliance with Attachment 10 of the Rocky Flats Cleanup Agreement (RFCA) (CDPHE, 1996) and achieve the best possible performance related to multiple project goals, which include:

- General regulatory compliance and demonstration of performance equivalent or better than that of standard regulatory designs
- Adherence to quality objectives while assuring that the cover design is the best for site-specific climate, soils, and vegetation
- Integration with overall Rocky Flats Environmental Technology Site (RFETS) closure configuration
- Sustainable vegetation, minimal erosion, and maximized design life with minimal long-term care
- Adherence to surface water, groundwater, and air quality objectives and protection of wetlands and endangered species habitat
- A design that is soundly engineered, constructible, and cost-effective

Performance modeling has been undertaken to support the conceptual design and to demonstrate the performance of an ET cover with respect to minimizing infiltration through the cover. The performance modeling approach and results are provided in Appendix A of the

Conceptual Design for the Present Landfill Closure Cover Rocky Flats Environmental Technology Site (Conceptual Design Report). The purpose of this feasibility report is to summarize the project findings and establish that, based on the results of the study, an ET cover is a viable system for closure of the Present Landfill.

B.2 Determination of Feasibility

ET cover designs have been undergoing technical development and have gained more widespread regulatory acceptance in recent years. ET cover applications have included both hazardous waste landfills (Resource Conservation Recovery Act [RCRA} Subtitle C) and municipal landfills (RCRA Subtitle D). For example, the ET covers for Landfills 5 and 6 at Fort Carson in Colorado, which were approved by the Colorado Department of Public Health and Environment (CDPHE), were designed to meet Subtitle C requirements (Earth Tech Environment and Infrastructure, Inc., 2000). A number of long-term ongoing field studies have provided data substantiating the performance of ET covers. Many of these projects have been conducted in association with the EPA's Alternative Cover Assessment Program (ACAP). Additional details on ET cover technological developments are provided in Appendix C of the Conceptual Design Report.

Alternative cover performance standards and requirements vary greatly across the western U.S. Performance standards from other states with similar semi-arid climates provide some design guidance to evaluate ET cover performance. California standards for equivalence are site-specific and have allowed up to 1 inch per year (inch/yr) percolation. Utah may soon permit a site where equivalent performance allows up to 8 centimeters (3 inches) of percolation. New Mexico defines equivalent covers as those that are within an order of magnitude percolation of the conventional cap at the low percolation values often obtained (i.e., since percolation values for conventional covers are often 0.01 inch/yr or less, New Mexico would define an equivalent cover as one with low percolation of 0.1 inch/yr or less). Arizona sites can meet the equivalence criterion by demonstrating upward flux using numerical models. Nebraska will soon examine existing local ACAP data from Omaha and will likely make a decision to approve a nearby alternative cover based upon qualitative evaluation of the data (see Appendix C of the Conceptual Design Report).

B.2.1 ET Cover Suitability

The primary factors that determine suitability of an ET cover at a given site are the characteristics of the site itself. Specifically, local climate, vegetation, and soil must all have suitable characteristics so a successful ET cover system can be designed and implemented.

B.2.1.1 Site Characteristics

Rocky Flats is located in central Colorado on the eastern slopes of the Rocky Mountains. The Present Landfill location is shown on the RFETS Site Map in Figure B-1[KWA1]. The Present Landfill consists of a waste disposal area of approximately 21 acres with an additional 9 acres of buttress and pond. A landfill site plan is provided in Figure B-2[KWA2]. Site specific data were gathered from many sources including RFETS reports, public domain records such as weather records, and data from analyses carried out as part of this project.

B.2.1.1.1 Climate. Fairly complete climatological data are available from the Denver Stapleton Airport, where such data have been collected since the late 1940s. Individual precipitation events vary between the airport and RFETS, but long-term trends, variability, and averages are similar. Therefore, climatological data collected from Denver Stapleton Airport were used as input for UNSAT-H modeling of the RFETS ET cover (Appendix A of the Conceptual Design Report). Average rainfall for the area is 15 inch/yr with the heaviest events occurring in the months of June through September. Average annual pan evaporation in central Colorado is approximately 55 inches, an indication that potential evaporation from the soil is high. Typically, 10 to 20 percent of precipitation occurs during the winter months when much of the vegetation is dormant.

Data from Denver Stapleton Airport do not reflect known differences in wind speed and the decrease in solar radiation due to RFETS' proximity to the mountains. Both of these factors affect the water balance calculated by UNSAT-H. The stronger winds found at Rocky Flats will increase evaporation and transpiration, while the reduced solar radiation in late afternoons will reduce evaporation and transpiration. The decrease in solar radiation due to the mountains will be smaller than differences seen between natural or engineered north and south slopes. The

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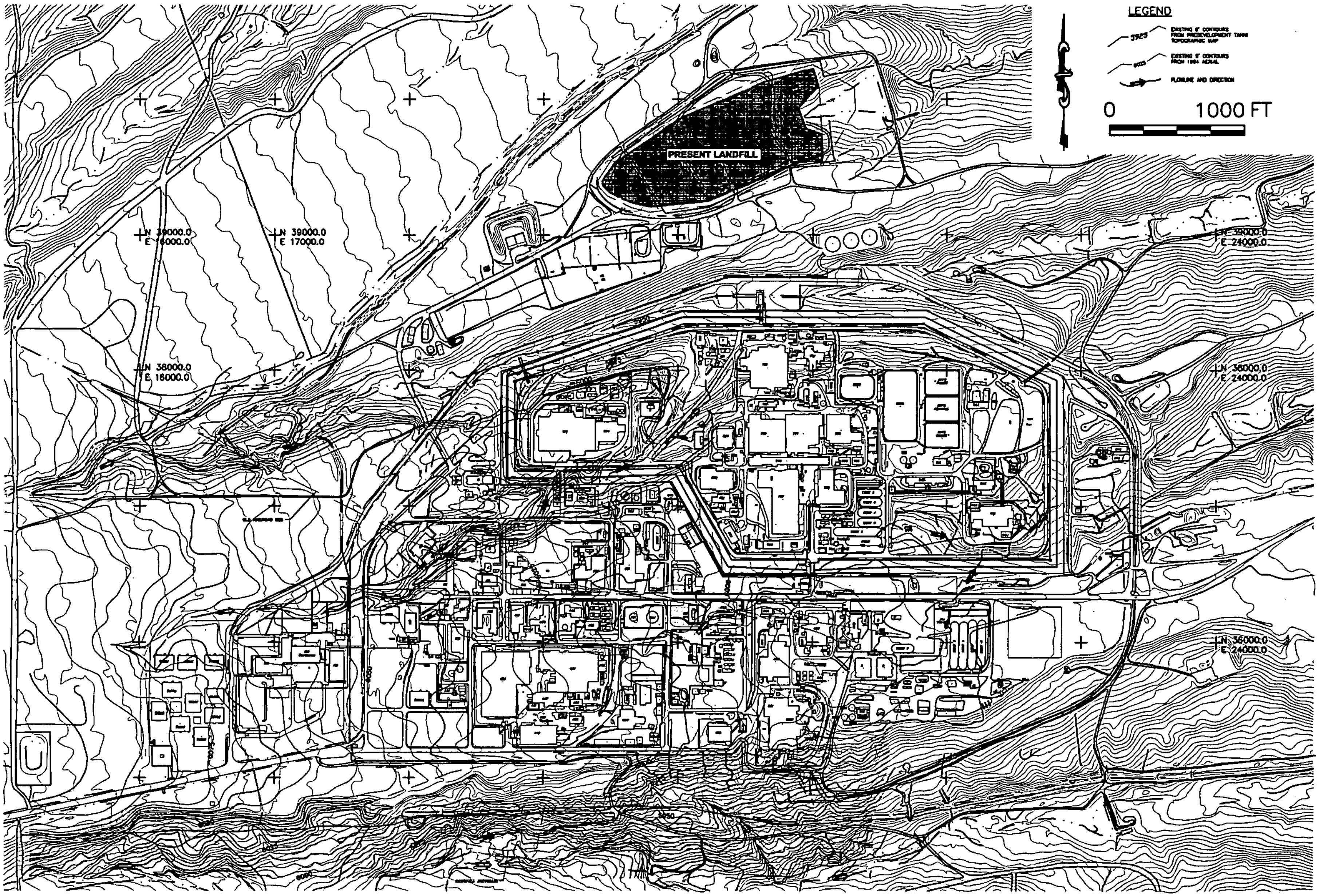

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Present Landfill Site Location Map

Figure B-1

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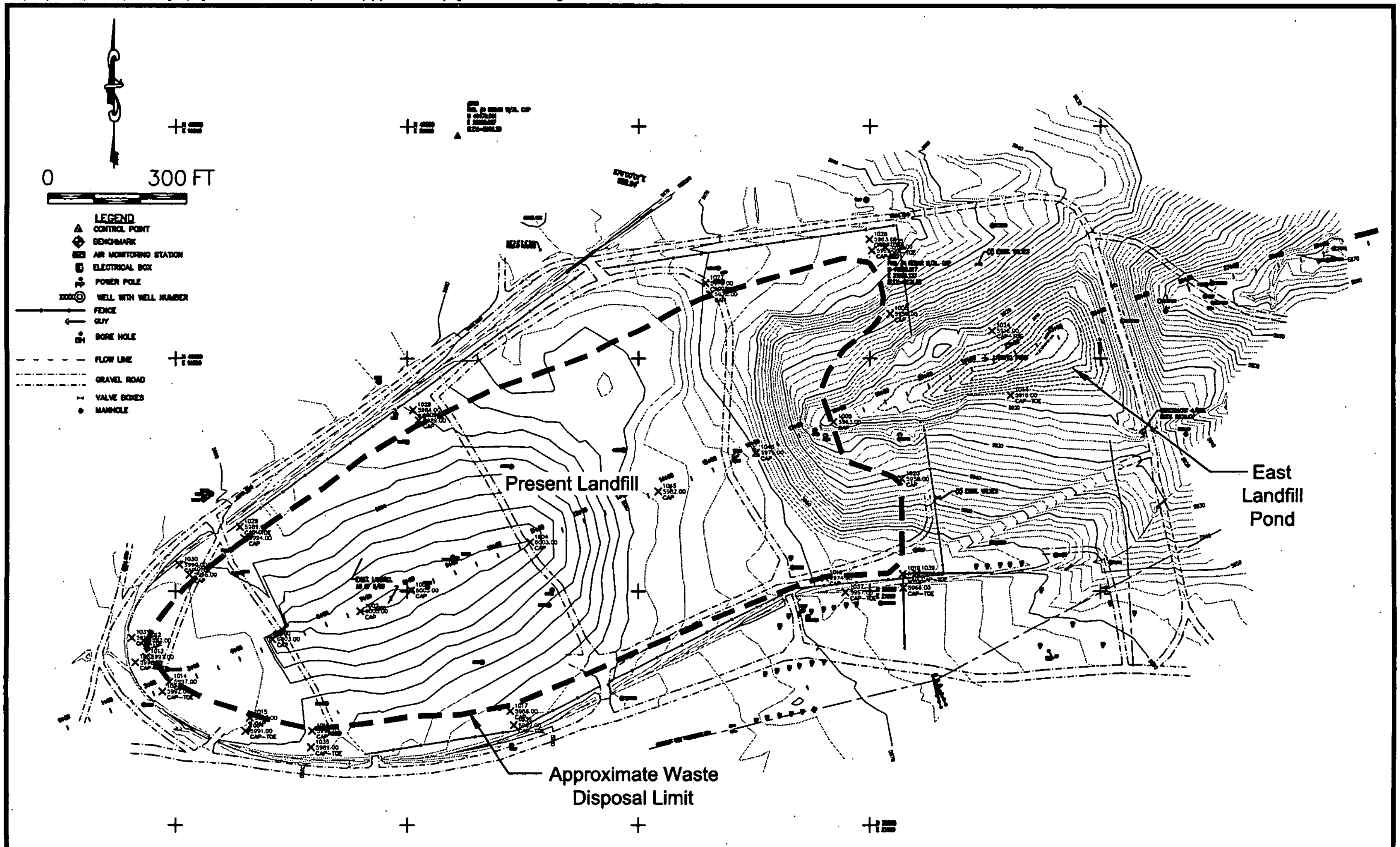


ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Present Landfill Site Plan

Figure B-2

west-facing slopes that may be most affected by reduced evening solar radiation will receive the largest 'benefit' of increased drying from down-canyon winds.

B.2.1.1.2 Vegetation. Native prairies at mid-latitudes such as those found in Colorado always have a mixture of both warm and cool season vegetation. The balance between these vegetation types at a given location is dynamic. Cool winters and dry summers result in a larger fraction of cool season vegetation cover. Cool season grasses typically have a more fibrous root system while warm season grasses are more deeply rooted. The dynamic is also affected by microclimates such as those on north- or south-facing slopes. Inspection of the RFETS site conducted for the ET cover conceptual design showed vegetation consistent with the native prairies of central Colorado. Consistency in plant species composition is well-documented in soil surveys along the Front Range. The mixture of plants with varying rooting strategies and depths is a common theme at other ET cover sites throughout the western U.S.

More details on the vegetation plan for the Present Landfill ET cover are provided in Volume I of the Conceptual Design Report (Section 4). Table A-2 in Appendix A of the Conceptual Design Report provides typical rooting depths for specific plant species. The rooting depth and distribution data should be interpreted carefully because root systems are dynamic and root water uptake occurs where and when the water is available. The common advice to water lawns more deeply and less frequently to encourage deeper rooting also applies to variations in rooting patterns caused by changes in rainfall patterns. Available numerical models are not proficient in tracking this variability in rooting profiles. However, agronomic evaluation of cover performance generally supports numerical evaluations.

B.2.1.1.3 Soil. An investigation was conducted to characterize, sample, and test the typical borrow soil available from sources near RFETS, for possible use in constructing the ET cover. Appendix J of the Conceptual Design Report contains a summary of the geotechnical properties for soils tested as part of this project. Soil was sampled from the LaFarge Quarry adjacent to the northern RFETS boundary, a possible off-site source of borrow soil for cover construction. This soil is from the same soil series common on-site at RFETS. The soil is characterized as a sandy loam using the U.S. Department of Agriculture (USDA) soil classification and clayey sand with gravel using the American Society for Testing and Materials (ASTM) soil classification.

Laboratory analysis revealed the following soil characteristics:

- Calculated porosity of the soil is 38.6 percent by volume
- Dry bulk density of the material is 1.63 grams per cubic centimeter (g/cm^3)
- Saturated hydraulic conductivity is 5.1×10^{-4} centimeters per second (cm/s)
- van Genuchten parameters for this sample are:
  - $\alpha = 0.0438$
  - $N = 1.37$
  - residual moisture content (θ_r) = 0.11
  - saturated moisture content (θ_s) = 0.38

The soil data were input into UNSAT-H, using the van Genuchten function model option (van Genuchten, 1991) to simulate the ET cover performance.

The sandy loam from the LaFarge Quarry is similar to soils used at Rocky Mountain Arsenal (RMA) and Fort Collins in alternative ET covers. RFETS has yet to determine a source of borrow material for the proposed cover on the Present Landfill. Although large volumes of suitable material appear available nearby or on-site, any proposed material needs to be characterized and the design profile re-evaluated numerically during the final design phase of the project.

B.2.1.2 ET Cover Research Results

There are several projects in the western U.S. that are evaluating the applicability and performance of alternative cover systems such as the one being proposed for the Present Landfill. A review of results from two ongoing federally supported programs and information on regulatory and testing requirements from numerous sites testing or using alternative covers in the western U.S. is summarized below. Additional details are provided in Appendix C of the Conceptual Design Report.

B.2.1.2.1 Alternative Landfill Cover Demonstration (ALCD). The ALCD is a large-scale field test at Sandia National Laboratories, located on Kirtland Air Force Base in Albuquerque, New Mexico. Funded by the U.S. Department of Energy (DOE), the ALCD is examining alternative cover performance for several alternative cover designs suitable for arid and semi-arid climates. Construction and instrumentation is complete and the ALCD is now in the performance-monitoring phase.

Early on, the ALCD committee (which includes representatives from the Western Governors Association and the DOE) decided that a goal of the project would be to develop a general data set to be used throughout the arid and semi-arid regions of the country. These data could then be used in the development of alternative covers based on the design principles used in the ALCD test covers. The side-by-side arrangement of the test covers, the cover profiles used, the monitoring schemes deployed, and the size of the test covers were all decided upon by the ALCD committee with input from state regulatory agencies and the EPA. The ALCD committee met with regulators and other stakeholders periodically to discuss progress and ensure that the data set being developed would be adequate to demonstrate compliance with all federal and state requirements. The early and continual involvement of regulatory agencies has resulted in the ALCD gaining national recognition and acceptance.

B.2.1.2.2 Alternative Cover Assessment Program (ACAP). The goals of ACAP, an EPA-sponsored project, are to (1) evaluate the performance of alternative earthen final cover (AEFC) systems for closure of solid waste landfills, (2) compare the performance of AEFCs to conventional cover designs and (3) provide a better understanding of the behavior of near-surface soil-plant-water-atmosphere systems. The ACAP data collected include in situ, continuous measurement of precipitation, surface runoff, deep percolation, volumetric soil-moisture content, soil-moisture potential, soil temperature, solar radiation, air temperature, relative humidity, wind speed, and wind direction. The 12 ACAP sites are located in 8 states across the country and include a broad cross-section of the physical environments represented within the continental U.S.

The ACAP program operates research-grade monitoring stations to improve understanding of the dynamics and interactions between soil, plant communities, atmospheric parameters, and moisture in the near-surface environment that comprises final landfill covers. Construction of ACAP sites was completed in late 2000 with locations near (in chronological order) Sacramento, California; Polson, Montana; Helena, Montana; Cincinnati, Ohio; Logan, Ohio; Albany, Georgia;

Marina, California; Monticello, Utah; Omaha, Nebraska; Livermore, California; Cedar Rapids, Iowa; and Boardman, Oregon. The ACAP program was designed to evaluate the performance of both conventional and alternative cover designs in a side-by-side comparison.

Three sites in the ACAP program (Sacramento, California; Polson, Montana; and Helena, Montana) were constructed in 1999. The remaining seven sites were constructed in 2000. ACAP data are preliminary due primarily to the immature state of the vegetation on the covers. Unlike conventional covers, which rely on soil and geomembrane material parameters for their performance, alternative covers depend on transpiration from established plant communities to remove moisture from the cover profile. As of spring 2001, the following observations had been made:

- The lysimeters at Sacramento had not drained sufficient quantity to record by the dosing siphons, indicating that minimal infiltration has occurred. Resolution of the dosing basins is 0.5 millimeters (mm) across the surface of the lysimeter.

- The alternative cover at Helena, Montana also had not recorded sufficient infiltration to trigger the dosing siphons.

- The alternative cover at Albany, Georgia demonstrated better performance than the compacted clay cover.

- The conventional cover at Monterey, California (a composite of compacted clay and a 60-mil geomembrane) was producing drainage.

B.2.1.3 ET Cover Suitability

The primary regulatory consideration for ET cover approval is to demonstrate that infiltration reduction performance is equivalent to conventional designs. ET covers are considered alternative designs to the standard designs specified by state and federal regulations. Regulations provide for alternative cover design approaches based upon a demonstration of performance equivalent to the standard design. The standard cover design includes a flexible membrane liner (FML) overlying a 2-foot compacted clay layer to minimize infiltration. However, for the RFETS application, the conventional design has two significant drawbacks: (1) the synthetic FML has an uncertain longevity and may not achieve the desired design life, and (2) compacted clay covers desiccate and crack in semi-arid conditions. The ET cover alternative design should provide superior infiltration reduction and longevity performance for final closure of the RFETS Present Landfill.

Evaluation of the site's climatic conditions, vegetation, and soil characteristics indicate that the RFETS area has all the conditions and materials needed to design and build a successful alternative ET cover.

B.2.1.4 ET Cover Acceptance

Alternative vegetated landfill covers have been deployed at many sites in the western U.S. in the past several years because of their relatively low cost and generally good performance. Gaining regulatory acceptance of alternative covers was initially difficult because of lack of field performance data. Early projects often required extensive demonstration of the proposed alternative cover.

Because of the demonstration requirement, only large sites such as Rocky Mountain Arsenal (RMA) could support the cost and time of such a demonstration. For example, the extensive research and regulatory review process performed over the past six years to develop and demonstrate the efficacy of alternative covers at RMA has cost over a million dollars. A preliminary estimate of the cost to build a demonstration at RFETS similar to those now being tested by the ACAP is approximately $300,000 (DRI, 2001). With five years of monitoring costs, assessments, and reports the total effort would likely approach $500,000, even after all the 'spadework' done by RMA. Although cost is a factor, the greatest impact is time. Due to the accelerated nature of RFETS closure, meaningful data could not be obtained from a demonstration to support the cap construction before the 2006 closure date. ET covers have been constructed in Colorado without construction of a demonstration area. The landfills at Fort Carson were constructed without a demonstration area; instead, performance monitoring will be used to ensure the cover performance.

B.2.1.5 Geotechnical Considerations

A geotechnical evaluation of slope stability was undertaken as part of the ET cover conceptual design. This evaluation shows that the cover is stable under both static and dynamic conditions. The proposed ET cover is designed with relatively gentle slopes of less than 14 percent, which will promote both slope stability and erosion resistance.

At the conceptual design stage, selection of suitable slopes for the ET cover is based on existing geotechnical studies completed for sites at RFETS with similar characteristics. The maximum ET cover slope is based largely on the findings of an earlier geotechnical study presented in *Geotechnical Investigation Report for Operable Unit No. 5*, (DOE, 1995). The site within Operable Unit No. 5, referred to as the Original Landfill, was characterized by unstable slope conditions. This study found that slopes of 14 percent (7:1) are stable for Rocky Flats Alluvium overlying weathered claystone, in an area of shallow groundwater and seeps. These conditions are similar to those at the Present Landfill.

The maximum cover slope for the Present Landfill is much less than the typical slope design at other types of waste disposal facilities, such as municipal landfills or mine tailings impoundments. These facilities often use slopes of 25 percent (4:1) to 33 percent (3:1). In some cases steeper slopes are used, with appropriate slope stabilization methods. In comparison, the gentle ET cover slopes proposed are not only feasible, but are relatively conservative with regard to slope stability.

A complete evaluation of geotechnical considerations during the final design stage should include linking the ET cover design with studies currently underway at RFETS to evaluate shallow groundwater conditions and control. It is recommended that an additional geotechnical evaluation be completed that examines slope stability, with site-specific shallow groundwater and hydrogeologic conditions included in the analyses.

B.2.2 Environmental Performance Considerations

B.2.2.1 ET Cover Performance

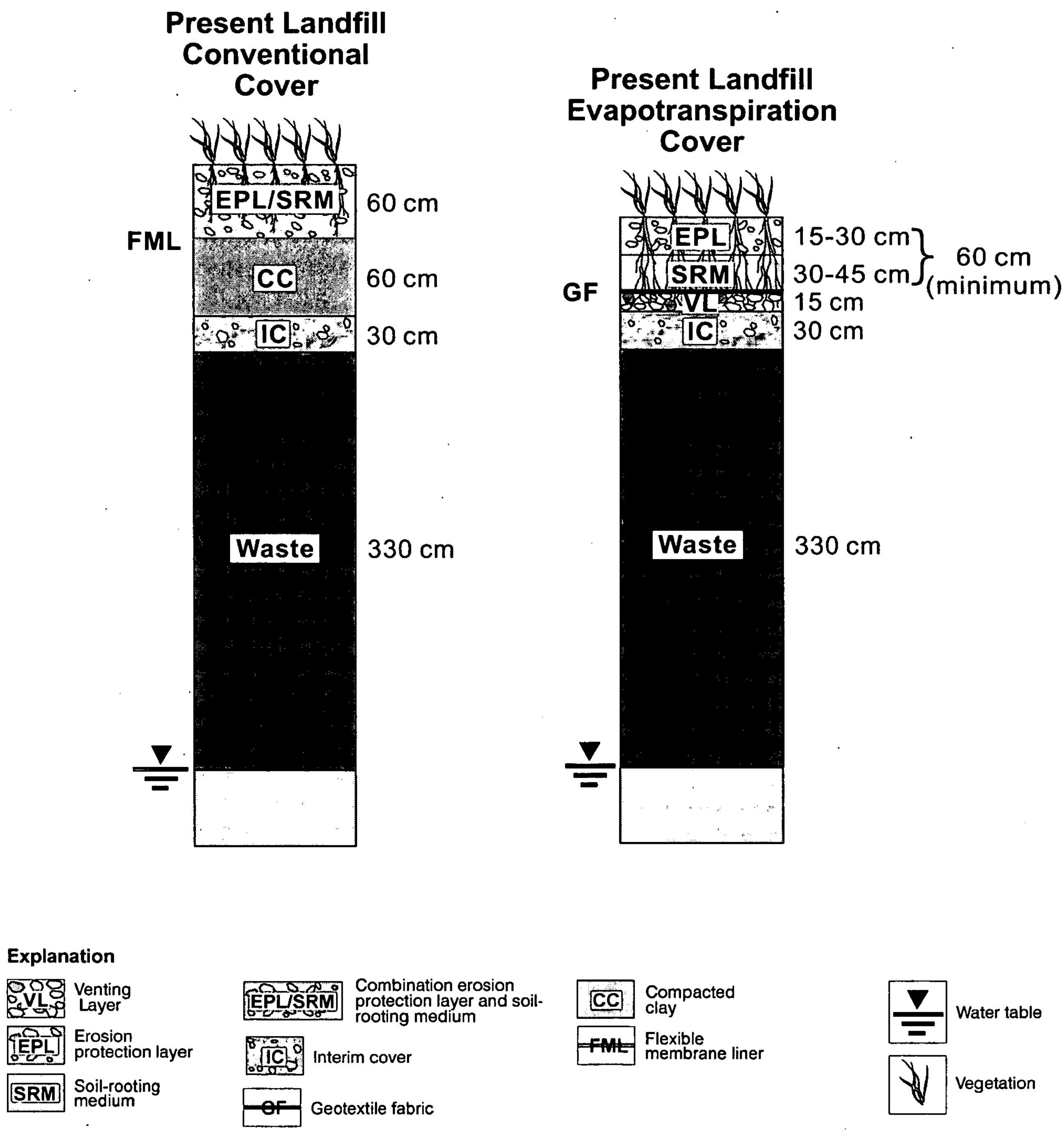
Water balance modeling uses a soil's water-holding capacity characteristics to determine the cover thickness adequate to reduce infiltration. The modeling discussed in this report compares the ET cover's effectiveness to that of a conventional cover consisting of synthetic and clay barrier layers. The UNSAT-H model was used for the ET cover performance modeling. UNSAT-H is a widely accepted and used, physically based model that accurately describes water movement and redistribution in unsaturated soils systems such as landfill covers. Appendix A of the Conceptual Design Report contains the modeling report for the ET cover using UNSAT-H. Appendix D of the Conceptual Design Report contains the model selection report.

The Present Landfill ET cover will consist of a multilayered system (Figure B-3[KWA3]) with the major component being a rooting medium soil layer that consists of borrow material with the characteristics described in Section 2.1.1.3, that is, a loamy soil with gravel. For numerical modeling, a combination of an erosion protection layer that will also support vegetation and a soil-rooting medium was placed over the existing profile. In addition a 6-inch methane-venting layer was included below the soil-rooting medium. In the alternative cover cross-section, the erosion protection and soil-rooting medium layers will be separate layers with a combined thickness of at least 2 feet (Figure B-3), while the average thickness of these layers will be more than 5 feet based on the conceptual final cover grading plan. The erosion protection layer will vary from a minimum of 6 inches on gently sloping areas (minimum 3 percent slope) and up to 12 inches on areas where additional erosion protection is needed (maximum 14 percent slope).

A comparison of percolation through the ET cover and the conventional cover indicated that the percolation rates in the ET cover were approximately the same as those in the conventional cover.

This performance modeling demonstrated the following:

- The proposed 2-foot-thick ET cover is equivalent to the conventional cover.



ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Modeled Cover Cross-Sections

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Figure B-3

- Percolation through the ET cover is essentially zero.

- Local soil is available and suitable for the proposed ET cover system.

- Native vegetation and proposed vegetation will be suitable for the proposed ET cover.

- Thicker covers, up to approximately 60 centimeters (24 inches), significantly improve performance. Beyond 60 cm, little added performance benefit is seen.

- Modeling of the effects of rooting depth shows that a venting layer is needed at the Present Landfill to provide oxygen to plant root systems, so that proper rooting depths can be established.

These results are consistent with nearby research experience at RMA and support the conclusion that the potential for water percolation through the RFETS ET cover is low.

B.2.2.2 Control of Contaminant Mobility

The Present Landfill must be closed under the provisions of Attachment 10 to the RFCA. The most significant RFCA compliance issues are related to the quality of shallow groundwater and surface water at the eastern, downgradient end of the landfill. A seep at the toe of the eastern landfill slope discharges an average of 2 gallons per minute through a passive aeration treatment system and into the East Landfill Pond. Reduction in contaminant mobility is achieved by the ET cover primarily by reduction of percolation through the existing cover. A proposed ET apron immediately downgradient of the landfill can provide backup control of any seepage from the landfill. In accordance with RFCA, downgradient and downstream points of compliance will need to be established.

B.2.2.3 Effectiveness

The site characteristics needed to design and implement a viable ET cover are all present at the RFETS site. Climatic conditions are favorable being located in an area with low precipitation, with the dry conditions also contributing to high potential evaporation. Vegetation in the area has adapted to local environment and has rooting and growth characteristics that will create a dense root mass capable of removing large amounts of water from the cover system. Finally, the soil has a moderate hydraulic conductivity and sufficient water-holding capacity such that infiltration water will be held within the cover for removal by evaporation and transpiration.

Soil-geomorphic relationships can support the design and placement of long-term waste containment systems such as landfill covers. Geomorphic investigations of the Rocky Flats Alluvium indicate that (1) the surface has been stable for greater than 1.3 million years, and (2) these rocky soils have a favorable water balance. It can be inferred that a landfill built in Rocky Flats Alluvium with a cover that mimics the morphology of the alluvium will likely survive for 1,000 or more years.

The earthen materials used in the conceptual design are intended to meet a 1,000-year design life criterion. Synthetic materials are used in the conceptual design only to provide venting for landfill gas at the Present Landfill. Landfill gas is generated through waste decay, which is a relatively well-understood phenomenon that leads to nearly complete waste degradation and cessation of gas generation over a relatively short timeframe. Landfill gas generation modeling for the Present Landfill (described in the Conceptual Design Report, Section 3.2.4) indicates landfill gas generation will decline to minimal rates over the next 25 to 75 years. The synthetic materials included in the conceptual cover design will serve their intended short-term function and are not required to have longer-term performance.

B.2.3 Implementability

The ET cover conceptual design is practical and feasible to implement as a component of the final closure plan for the Present Landfill. Various aspects of project implementability are addressed in this section.

B.2.3.1 Materials Availability

The ET cover for the Present Landfill will be constructed primarily of native geologic materials that are readily available and possess relatively common properties. The ET cover design allows for a range of soil and rock properties that will provide suitable performance, and the ability to optimize the design by adjusting layer thickness to account for specific properties of selected materials.

A variety of potential sources of soil and rock materials are available in off-site commercial quarries and on-site borrow areas at RFETS. Final determinations of material sources will require additional testing of actual materials proposed for use and design optimization to accommodate the properties of available materials within the ET cover design.

Many of the materials used for the soil-rooting medium, erosion protection, and methane-venting layers are available on-site. The Flatirons Series surficial soils and Rocky Flats Alluvium in the shallow subsurface contain loamy soils with a significant clay fraction, which provide good moisture retention characteristics. The on-site soil and alluvium also contains a large fraction of gravel and cobble-sized rock, which can be used to reinforce the upper erosion protection layer and the gas-venting layer.

The conceptual design provides an approach for an extension of the ET cover, referred to as the ET apron, which will provide a source of soil materials as well as a treatment system to eliminate the existing seep. The ET apron size and elevation can be designed to provide a soil balance to match excavation and cover soil quantities, providing an efficient and cost-effective design. Thus, the conceptual design approach incorporates a built-in mechanism to optimize the final design with regard to quantities and costs.

Materials required from off-site sources include synthetic materials used in the landfill gas-venting system, the seed mix, and possible soil amendments. Synthetic materials used in the gas-venting system will be obtained from commercial, off-site suppliers. These materials include geotextile separation fabric and HDPE or other piping materials, which are readily available. Seed mix and possible soil amendments will be procured from off-site sources based on seed specifications and soil nutrient needs. Seed mix specifications will meet KH Ecology Group requirements, with consideration of the seed species that can be reasonably obtained.

B.2.3.2 Constructibility

The conceptual design of the Present Landfill ET cover provides for standard construction methods. The earthwork, aggregate placement, piping installation, geosynthetics installation, and revegetation associated with construction of the cover are all common practices in the U.S. construction industry. The majority of the construction effort will be earthwork, using conventional heavy equipment, to place the soil-rooting medium, erosion protection, and aggregate layers.

Construction methods will vary depending on whether on-site or off-site soil borrow sources are selected, both of which are feasible options. On-site borrow will require excavation and processing to screen rock and aggregate materials. On-site materials processing is common construction practice and can be effectively set-up for short-term operation. Off-site borrow will require that suitable haul routes be established to transport materials from commercial quarries. Transport from an off-site source may involve hauling over public roadways or constructing a dedicated haul road from the construction site to the LaFarge Quarry located adjacent to the northwest RFETS boundary.

Access routes and transportation plans to haul soil from off-site sources is a key constructibility issue, if large soil quantities for the major cover components are imported. The material quantities for this project are significant, and depending on the design options selected and quantity of off-site materials used, many thousands of truckloads of material may be shipped. Possible restrictions on the number of haul trucks allowable on public roadways may be a limiting factor in the construction schedule.

The ET cover must be constructed in a manner that limits compaction to provide a suitable soil-rooting medium to establish vegetation. Soil compaction will be limited to approximately 80 to 90 percent of Standard Proctor density. Unlike typical earthwork, compaction of soils will not be needed, which will require low ground pressure equipment and carefully planned placement and haul routes. As needed, any over-compacted areas will be ripped and loosened during the final soil preparation.

The construction methods needed for the Present Landfill ET cover follow industry standards for cover construction and general earthwork projects. Because the construction methods are straightforward and uncomplicated, there are many qualified and competitive contractors capable of performing this work.

B.2.3.3 Schedule

The schedule for construction of the ET cover is expected to take 8 to 10 months to complete. The construction schedule could probably be compressed by 1 to 2 months, if an aggressive approach is taken for construction activities and the required equipment is mobilized to the site. Any on-site processing of soils to generate gravel and rock materials may require significant timelines; therefore, soil quantities and screening capabilities should be considered carefully in the schedule.

The construction schedule assumes selection of a reasonably close soil borrow site, either on-site or within a short haul distance, where soil can be obtained in quantities required for an efficient construction sequence. An extended construction schedule may be necessary if transport of off-site soils is limited due to highway restrictions. Construction could proceed efficiently, if at a slower pace, as long as materials can be provided at a rate that keeps a reasonably sized personnel crew and equipment fleet continually active, without delays.

In addition to the construction timeframe, the overall project schedule includes the following additional engineering activities:

- Geotechnical investigation to select final soil borrow sources
- Final engineering design
- Contracting and construction administration
- Construction inspection and testing
- Final construction certification report

The entire project should be completed in approximately 18 to 24 months. This schedule is ample for the engineering design and construction of typical landfill cover projects.

The scheduling timeframes for RFETS are much more uncertain. The two-year project schedule includes final engineering design and construction, but does not include the current review and approval process. This is because the approval process is linked to many other projects, issues, and decisions in the in the overall context of Present Landfill final closure as a component of site-wide RFETS closure plans. Project success and schedule may hinge on issues that are unforeseen at this point. The schedule provided is based on unimpeded design and construction progress after all regulatory approval processes are complete.

Following construction, a rigorous performance-monitoring phase lasting approximately six years is planned. The ET cover will take approximately three to four years for vegetation to become fully established. Performance monitoring to determine the successful performance of the ET cover to remove soil moisture through plant transpiration will need to continue until after the vegetation is fully established. After successful performance is demonstrated, the monitoring requirements are expected to be gradually scaled back, until all monitoring can be terminated once steady-state performance is achieved.

B.2.3.4 Cost Projections

The project cost for engineering and construction of the Present Landfill ET cover is estimated to be approximately $10.2 to $11.2 million, depending on borrow source and waste relocation decisions. In addition, long-term monitoring and maintenance for a period up to 30 years is expected to cost approximately $650,000. This figure is not adjusted for present worth. These cost projections are for direct engineering, construction, and monitoring costs, and do not include the regulatory permitting process currently underway. This cost estimate provides preliminary budgetary planning information to assist RFETS decisions on implementing the ET cover approach.

A key issue affecting the Present Landfill construction cost estimate is the possible relocation of the asbestos disposal areas. Based on asbestos-handling unit costs provided by KH, the asbestos relocation cost would be the most significant cost component of the overall construction cost. The cost for asbestos relocation hinges on very incomplete records of the quantity and location of asbestos materials. Additional research using available records or knowledge of RFETS personnel may help to better establish the history of asbestos disposal at the Present Landfill and determine whether the most cost-effective approach is to close the site with asbestos covered in-place or to relocate the asbestos to achieve a reduced final cover area.

The cost estimate is heavily dependent on the final soil borrow source selected. Off-site soil, imported to the site, will be more costly than on-site soils. Transportation costs escalate substantially as the haul distance increases. On-site and nearby soils at RFETS or off-site commercial quarries appear suitable for ET cover construction based on initial laboratory testing and modeling results. However, the cost estimate does not include a possible determination of the status of mineral rights and possible royalty costs for use of on-site soils. Final decisions on the soil borrow source location will be made after material specifications are developed and more extensive soil testing is completed. Whatever final borrow source is selected, suitable soils are available within reasonable haul distances to keep construction costs to a minimum.

B.3 Conclusions

The conceptual design project has evaluated all the traditional engineering aspects of the proposed closure of the Present Landfill, producing reasonable results and conclusions for all items investigated. Overall feasibility, however, is based on conclusions related to three basic areas of the conceptual design project that lead to the recommendation of an alternative ET cover as the preferred closure method at the Present Landfill:

- ET cover suitability
- Environmental performance
- Implementability

The following sections summarize results obtained in each of these areas and provide recommendations regarding further action that will lead to the successful design and implementation of an ET cover.

B.3.1 ET Cover Suitability

The primary factors that determine suitability of an ET cover at a given site are the characteristics of the site itself. Specifically, local climate, vegetation, and soil must all have suitable characteristics for an ET cover system to be designed and implemented successfully.

The site characteristics needed to implement a viable ET cover are all present at the RFETS site. Climatic conditions are favorable, since RFETS is located in an area with low precipitation, where dry conditions also contribute to high potential evaporation. General weather patterns of moderate to low rainfall and high evaporation rates, which are enhanced by high winds, are prevalent throughout central Colorado. RFETS climatic conditions are conducive for implementation of a successful alternative ET cover system.

Vegetation in the RFETS area is well-adapted to the local environment and has rooting and growth characteristics that will create a dense root mass capable of removing large amounts of water from the cover system. A mixture of plants with varying rooting strategies and depths is a common theme at ET cover sites throughout the semi-arid western U.S., including the RFETS area. Both cool season grasses, which typically have a more fibrous root system, and warm season grasses, which are more deeply rooted, are common species that would thrive in the RFETS area. A diverse group of plants with differing transpiration strategies and rooting patterns provides a stable vegetated cover.

Finally, locally available soils have a moderate hydraulic conductivity and moisture-retention capacity sufficient to hold infiltration water within the cover for removal by evaporation and transpiration. Soils from the LaFarge Quarry, a possible nearby source of borrow material for the ET cover, were classified as sandy loams. On-site RFETS soils showed well-developed, stable soil profiles with carbonate accumulation, which indicates low erosion rates and long-term control of percolation. RFETS has yet to determine a source of borrow material for the proposed cover on the Present Landfill, however, large volumes of suitable material appear available at the Lafarge Quarry and on RFETS property.

B.3.2 Environmental Performance

ET covers have the capability to store infiltrating water until vegetation can transpire the water back to the atmosphere during the growing season. The UNSAT-H modeling results indicated that an ET cover over the Present Landfill is capable of achieving upward flux or no flux during periods of above-average precipitation. A comparison of percolation through the ET covers and the conventional covers indicated that the percolation rates in the ET covers were approximately the same as those in the conventional covers, i.e. percolation through the ET cover is essentially zero. Thicker covers, up to approximately 60 centimeters (24 inches), significantly improve performance. Beyond 60 cm, little added performance benefit is seen. These results are consistent with nearby research experience at RMA and support the conclusion that the potential for water percolation at the site is low.

A seep at the toe of the eastern landfill slope discharges an average of 2 gallons per minute through a passive aeration treatment system and into the East Landfill Pond. A proposed ET apron immediately downgradient of the landfill can provide long-term control of any seepage from the landfill. In accordance with RFCA, downgradient and downstream points of compliance will be established.

Soil-geomorphic relationships provide evidence that helps with the design and behavior of long-term waste containment systems such as landfill covers. The soil morphology of the Rocky Flats Alluvium, and particularly the Stage III and IV carbonate development, indicate that (1) the surface has been stable for greater than 1.3 million years, and (2) these rocky soils have a favorable water balance. It can be inferred that a landfill built in Rocky Flats Alluvium with a cover that is very similar to the existing stable soils will likely survive for thousands of years.

B.3.3 Implementability

An ET cover is feasible for final closure of the RFETS Present Landfill and can be implemented in a practical manner. The cover will be constructed primarily of readily available native geologic materials with relatively common properties. Final design of the ET cover can accommodate a range of material properties by optimizing the layer thickness for specific properties of selected materials. Construction of the ET cover will use standard construction methods. Construction can be completed within approximately 9 months, with the entire ET cover implementation, including final design, materials testing, contracting, inspection, and final certification, completed within 2 years.

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Appendix C

Update on Alternative Cover Testing and Monitoring

Update on Testing and Monitoring Requirements for Alternative Landfill Covers in the Western United States

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Appendix C.

Update on Testing and Monitoring Requirements for Alternative Landfill Covers in the Western United States

Summary

Regulatory approval to proceed with alternative cover design and construction has been granted at many sites across the U.S. as longer term research continues to be gathered on cover performance. Although little long-term cover performance data currently exist, limited data from three ongoing federal programs suggest adequate performance of alternate soil covers in the western United States (U.S.).

Locally, the Rocky Flats Environmental Technology Site (RFETS) is similar to two Colorado sites: Fort Carson, where an alternative cover has been deployed with adequate performance to date, and Rocky Mountain Arsenal (RMA) where alternative covers are being evaluated. Climate, vegetation, and soils at these three sites are similar. Formal numerical analyses using UNSAT-H at Fort Carson and at RMA of these interacting factors are similar to preliminary numerical analysis at RFETS. Overall, a site comparison indicates that performance from an alternative cover at RFETS will be similar to that at Fort Carson and RMA.

Information collected from sites in Colorado and other western states supports the broad regulatory acceptance of alternative covers. Neither test plots nor numerical modeling can fully account for site-specific factors such as reduced root growth caused by landfill gas, although test plots can provide data on project performance that would account for actual soil proposed for use and site-specific climatic conditions. Due to the accelerated RFETS closure schedule, meaningful data could not be obtained from test plots before actual construction of the cover and site closure in 2006. Therefore, a rigorous three-phased performance monitoring program is recommended for the Present Landfill to include intensive, intermediate, and long-term, if required, phases. The monitoring program is described in Section 7 of the Conceptual Design Report.

This report will document the current status of research and actual implementation of alternative covers at similar sites to support numerical analysis results for the ET cover proposed for the Present Landfill.

C.1 Introduction

The objectives of this report are to (1) review the approaches to alternative cover deployment and monitoring at other sites, and (2) evaluate field monitoring of a constructed cover at RFETS as an alternative to monitoring of test plots. To these ends, results from three ongoing federally supported programs were reviewed. In addition, information on regulatory and testing requirements from numerous sites testing or using alternative covers in the western U.S., including Colorado, are summarized. Contact information is provided for both federal programs and individual sites.

Alternative vegetated landfill covers have been deployed at many sites in the western U.S. in the past several years because of their relatively low cost and generally good performance. Gaining regulatory acceptance of alternative covers was initially difficult because of lack of field performance data. Early projects often required extensive demonstration of the proposed alternative cover.

Because of the demonstration requirement, only large sites with long-term projects, such as RMA, can support the cost and time of such a demonstration. For example, the extensive research and regulatory review process done over the past six years to develop and demonstrate the efficacy of alternative covers at RMA has cost over a million dollars. A preliminary estimate of the cost to build a demonstration at RFETS similar to those now being tested by the Alternative Cover Assessment Program (ACAP) is approximately $300,000 (DRI, 2001). With five years of monitoring costs, assessments, and reports the total effort would likely approach $500,000, even after all the 'spadework' done by RMA.

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C.2 Federally Funded Alternative Cover Research Projects

Recognizing both the economic and ecological potential of alternative covers and the limitations of individual site schedules and budgets, the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA) have sponsored research projects to study wider application of alternative covers. Two current projects funded by these agencies are the Alternative Landfill Cover Demonstration (ALCD), which is examining alternative cover performance relative to DOE's landfills, and the ACAP, which is evaluating alternative cover performance for EPA's solid waste sites. The ACAP (http://www.dri.edu/Projects/EPA/boston-brochure2.html) is evaluating covers primarily for solid waste sites, and the cover technology is similar to ALCD (Rocky Mountain Arsenal test pads were a prototype for ACAP test pads). Both ALCD and ACAP are showing results favorable for alternative cover deployment. In addition to ALCD and ACAP, DOE has supported the Uranium Mill Tailings Remedial Action (UMTRA) project for about 20 years. This project also provides insight into alternative cover performance.

In general, as data from ALCD, ACAP, or local sites (e.g., RMA) have accumulated, the requirement for on-site test pads has abated. While ALCD and ACAP provide performance data, individual states must proceed with the details of permitting sites for alternative covers. Requirements for monitoring of final covers are determined on a site-by-site basis rather than on any fixed state standard. Many regulators wish to maintain this flexibility due to the differences in size, setting, and waste streams of landfills within a state (e.g., RMA vs. Fort Carson). Section 3 summarizes the approaches taken to alternative cover permitting in several western states. Section 4 presents an overview of regulatory requirements in the western states. The site descriptions in Attachment C1 give details of landfills in the western U.S. that are using alternative covers. Additional information can be obtained from the individuals listed in Table C-1 who have been researching alternative covers in recent years.

Table C-1. Scientists and Engineers with Alternative Cover Expertise

Contact	Experience Summary
Steve Dwyer (505) 844-0595	Mr. Dwyer oversaw the design and construction of DOE's alternative cover demonstration project and oversees its ongoing operation in Albuquerque. Steve is a civil engineer and has consulted on a number of alternative cover projects.
Jody Waugh (970) 248-6431	Dr. Waugh is in Grand Junction, CO and has worked for many years on vegetated covers for uranium mill tailing sites. He has done and is doing evaluations on covers that have been emplaced for many years in various locations.
Craig Benson (608) 262-7242	Dr. Benson is a professor of civil engineering at the University of Wisconsin-Madison. Craig is actively involved in alternative cover research and has consulted on a number of alternative cover projects.
Bill Albright (775) 673-7314	Mr. Albright is at Desert Research Institute in Reno, NV. Bill has installed nearly all the ACAP covers and cover instrumentation and works closely with EPA-Cincinnati on the ACAP project.
Steve Rock (513) 569-7149	Mr. Rock is the EPA Project Manager for the ACAP program and is based at the U.S. EPA National Risk Management Research Laboratory (NRMRL) in Cincinnati, OH. The EPA has committed to issuing annual performance reports for each ACAP site.

C.2.1 Alternative Landfill Cover Demonstration

The ALCD is a large-scale field test at Sandia National Laboratories (SNL), located on Kirtland Air Force Base in Albuquerque, New Mexico. Construction and instrumentation is complete and the ALCD is now in the performance-monitoring phase. The ALCD was originated to serve as a data source for all sites in arid and semi-arid climates. Funded by the DOE, the ALCD has been endorsed by the Western Governors Association (WGA). The WGA endorsement of $10 million is meant to assist in getting DOE research deployed at actual restoration sties throughout the country. Originally, the WGA endorsed four projects; however, the ALCD was the only one that was actually deployed. Consequently, the ALCD project has benefited from the entire $10 million allotted to the WGA.

Early on, the ALCD committee (WGA representatives and DOE representatives) decided that a goal of the ALCD would be to develop a general data set to be used throughout the arid and semi-arid regions of the country in the development of alternative covers based on the design principles used in the ALCD test covers. The side-by-side arrangement of the test covers, the cover profiles used, the monitoring schemes deployed, and the size of the test covers were all decided upon by the ALCD committee with input from state regulatory agencies and the EPA.

The ALCD committee met with regulators and other stakeholders periodically to discuss progress and ensure that the data set being developed would be adequate to demonstrate compliance with all federal and state requirements. The early and continual involvement of regulatory agencies has resulted in the ALCD gaining national recognition and acceptance.

C.2.2 Alternative Cover Assessment Project

The goals of ACAP, an EPA-sponsored project, are to (1) evaluate the performance of alternative earthen final cover (AEFC) systems for closure of solid waste landfills, (2) compare the performance of AEFCs to covers prescribed by the Resource Conservation Recovery Act (RCRA), and (3) provide a better understanding of the behavior of near-surface soil-plant-water-atmosphere systems. The ACAP data collected include in-situ, continuous measurement of precipitation, surface runoff, deep percolation, volumetric soil-moisture content, soil-moisture potential, soil temperature, solar radiation, air temperature, relative humidity, wind speed, and wind direction. The 12 ACAP sites are located in 8 states across the country and include a broad cross-section of the physical environments represented within the continental U.S.

ACAP Monitoring Stations. The ACAP program operates research-grade monitoring stations to improve understanding of the dynamics and interactions between soil, plant communities, atmospheric parameters, and moisture in the near-surface environment that comprises final landfill covers. Construction of ACAP sites was completed in late 2000 with locations near (in chronological order) Sacramento, California; Polson, Montana; Helena, Montana; Cincinnati, Ohio; Logan, Ohio; Albany, Georgia; Marina, California; Monticello, Utah; Omaha, Nebraska; Livermore, California; Cedar Rapids, Iowa; and Boardman, Oregon. The ACAP program was designed to (1) evaluate and compare the performance of AEFC and conventional cover designs; (2) provide measurements that can be compared and contrasted between the 12 ACAP sites; and (3) leverage EPA investment with contributions from site owners including private and public entities and federal agencies.

At most ACAP sites, the primary hypothesis matches the current regulatory requirement for an alternative cover; that is, the hydrologic performance of the alternative design will equal or exceed that of the appropriate conventional cover. In current engineering practice this requirement is confounded by two problems: (1) there are very few field-scale data sets indicating the performance of any type of cover design, conventional or otherwise; and (2) without field-scale performance data, predicted performance must be made on the basis of material parameters (i.e., the use of low-permeability clay, which neglects the propensity of clay to form macropores) or numerical simulations, which suffer from the lack of field-scale data. The ACAP program was designed to evaluate the performance of both conventional and alternative cover designs in side-by-side comparison.

Preliminary ACAP Data. Three sites in the ACAP program (Sacramento, California; Polson, Montana; and Helena, Montana) were constructed in 1999. The remaining seven sites were constructed in 2000. ACAP data are in a very preliminary state due primarily to the immature state of the vegetation on the covers. Unlike conventional covers, which rely on soil and geomembrane material parameters for their performance, alternative covers depend on transpiration from established plant communities to remove moisture from the cover profile. As of Spring 2001, the following observations have been made:

- The lysimeters at Sacramento have not drained sufficient quantity to record by the dosing siphons (indicating that minimal infiltration has occurred). Resolution of the dosing basins is 0.5 millimeters (mm) across the surface of the lysimeter.

- The alternative cover at Helena, Montana also has not recorded sufficient infiltration to trigger the dosing siphons.

- The alternative cover at Albany, Georgia is demonstrating better performance than the compacted clay cover

- The conventional cover at Monterey, California (a composite of compacted clay and a 60-mil geomembrane) is producing drainage.

C.2.3 Uranium Mill Tailings Remedial Action Project

The UMTRA project designed and constructed disposal cells at 19 sites across the U.S. This project has more long-term experience (20 years) in cover design than either the ALCD or ACAP project and lessons from UMTRA have been incorporated into both ALCD and ACAP. The design philosophy of cover systems used for long-term containment of hazardous and low-level radioactive wastes has undergone significant changes since the initial designs were conceptualized following passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978. The regulatory framework established design-based standards for the project, and the UMTRA project designed covers to control a suite of contaminant-release processes. Cover designs for the UMTRA project disposal cells evolved to reflect changes in U.S. EPA standards and changes in politics, economics, and the state of technology during the 20-year life of the project.

After EPA published draft groundwater quality standards in 1987, the UMTRA project refined the cover design approach and placed greater emphasis on designing low-permeability covers. However, permeabilities achieved in the field have generally been higher than those predicted by laboratory tests. Wetting/drying cycles, freeze/thaw cycles, and biological activity have all been identified as important in the observed laboratory-field discrepancies.

The UMTRA cover design philosophy shifted during the late 1980s and 1990s as DOE came to the realization that, in the absence of regular maintenance, ecological succession on engineered covers is inevitable. DOE began to refine engineering guidance to exploit beneficial ecological changes and to design covers that improve rather than degrade over the long term as inevitable natural processes act on the system. The recently completed alternative cover design at Monticello, Utah, is the product of this evolution of thinking. Ongoing monitoring is underway at this site.

C.2.4 Long-Term Performance Project

In addition to short-term performance issues most often addressed at waste sites, DOE created the Long-Term Performance (LTP) project in 1998 to evaluate how changes in disposal cell environments, both ongoing changes and projected changes over hundreds of years, may alter cover performance. The data from this project will benefit the next generation of covers at DOE sites and will ultimately support the preparation of new cover design guidance by EPA.

C.3 Site Characteristics of Alternative Covers in Colorado

Alternative covers have been proposed or built at three locations in Colorado: Rocky Mountain Arsenal, Fort Carson, and Rocky Flats. This section reviews climate, soils, vegetation, and other characteristics of these sites.

C.3.1 Climate

Colorado climate data were obtained from http://ccc.atmos.colostate.edu/. Weather data from the Stapleton airport, the Colorado Springs airport, and Boulder were used for this comparison. Boulder probably experiences more mountain effects on weather than Rocky Flats, but was the nearest weather station with reasonably complete weather data for comparison.

Annual and monthly mean temperatures for Denver, Colorado Springs, and Boulder are shown in Figure C-1. Average annual temperature is 50.4°F in Denver, 48.7°F in Colorado Springs, and 51.6°F in Boulder. Figure C-2 shows mean maximum annual and monthly temperatures for the three cities: 64.2°F in Denver, 62°F in Colorado Springs, and 64.7°F in Boulder. Figure C-3 shows mean minimum monthly temperatures for the three cities: 36.6°F in Denver, 35.3°F in Colorado Springs, and 38.4°F in Boulder. Colorado Springs is consistently several degrees cooler than the other two sites throughout the year. Boulder has slightly warmer winters and cooler summers than does Denver.

Figure C-4 shows mean monthly precipitation for the three cities: 15.62 inches in Denver, 16.40 inches in Colorado Springs, and 18.83 inches in Boulder. Differences in rainfall among the three sites are more pronounced than in temperature trends. Colorado Springs experiences peak rainfall in the summer months of July, and August. Denver rainfall peaks earlier in the year with May being the wettest month. Boulder data also peak in May and show higher average precipitation than Denver in every month except July.

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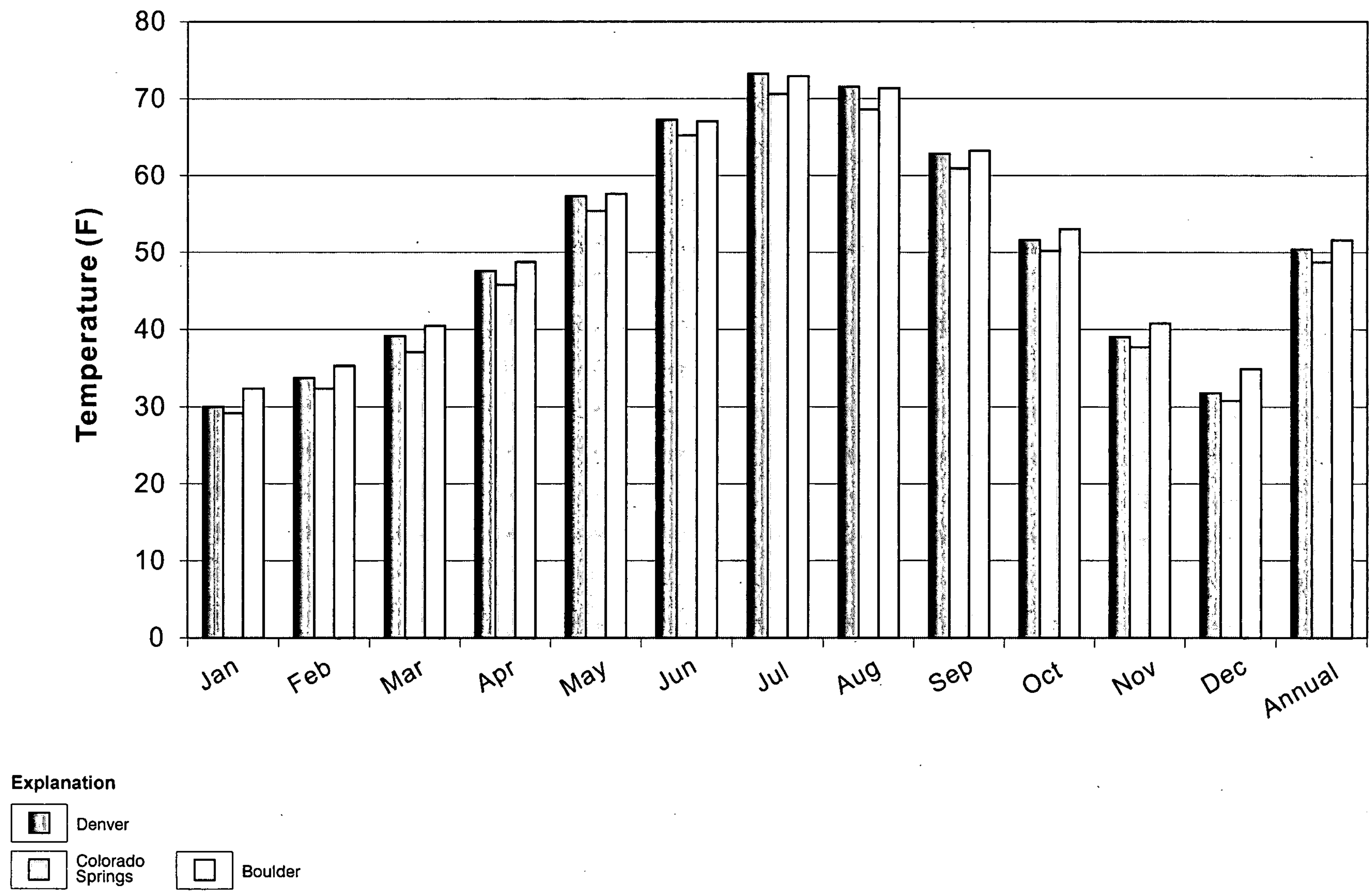

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Annual and Monthly Mean Temperatures

Figure C-1

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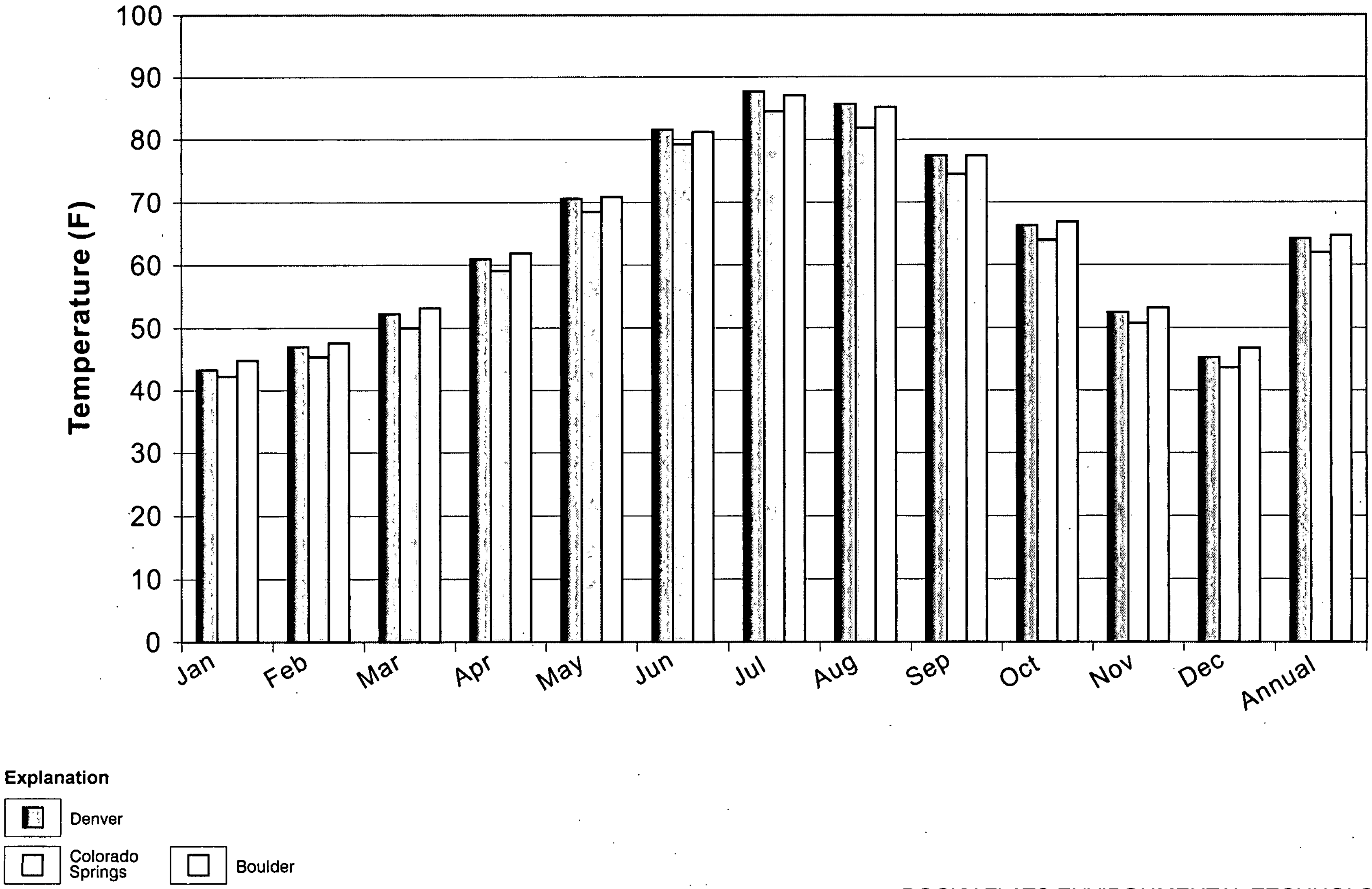

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Annual and Monthly Mean Maximum Temperatures

Figure C-2

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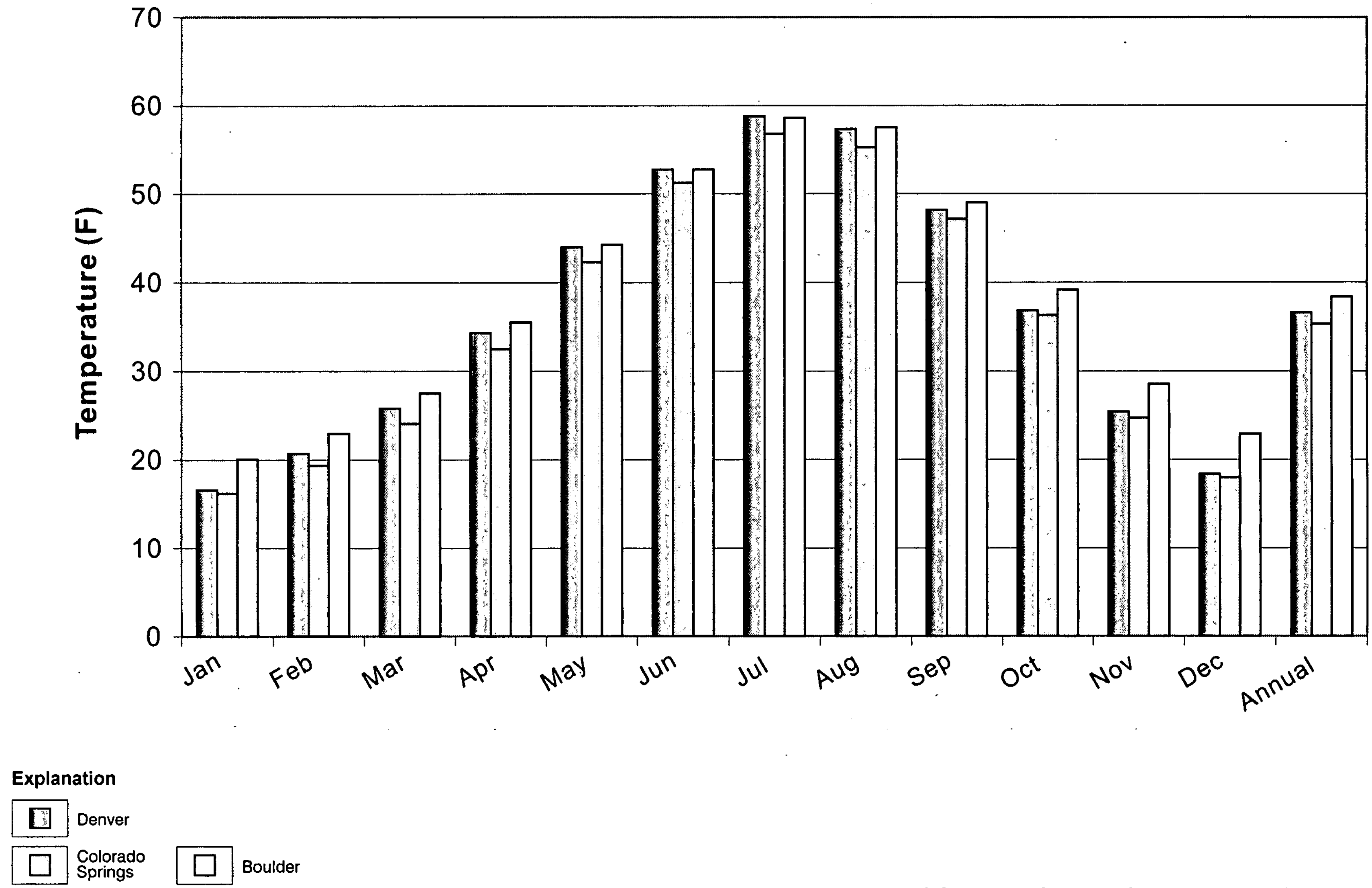

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Annual and Monthly Mean Minimum Temperatures

Figure C-3

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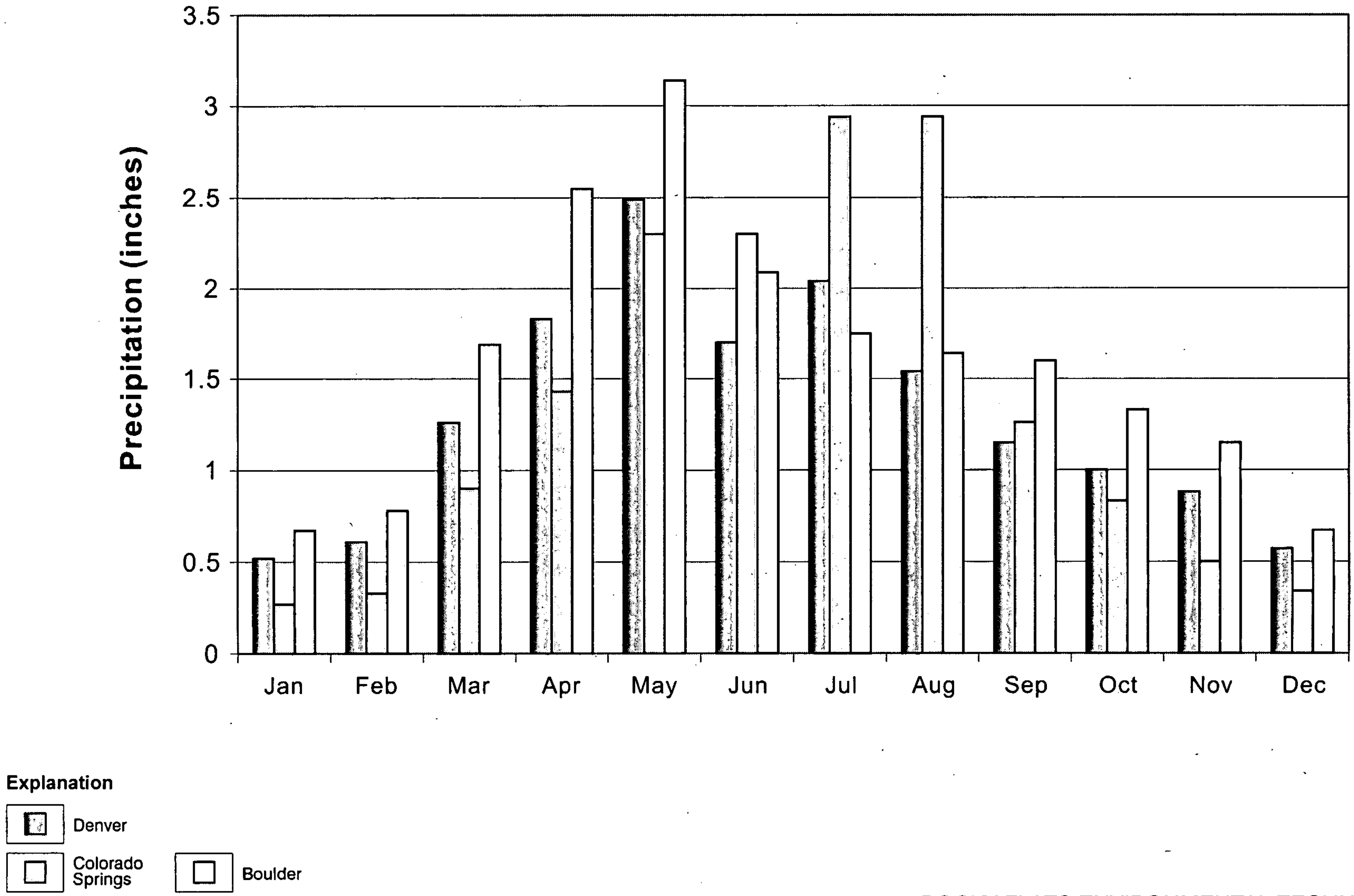


ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Monthly Precipitation

Figure C-4

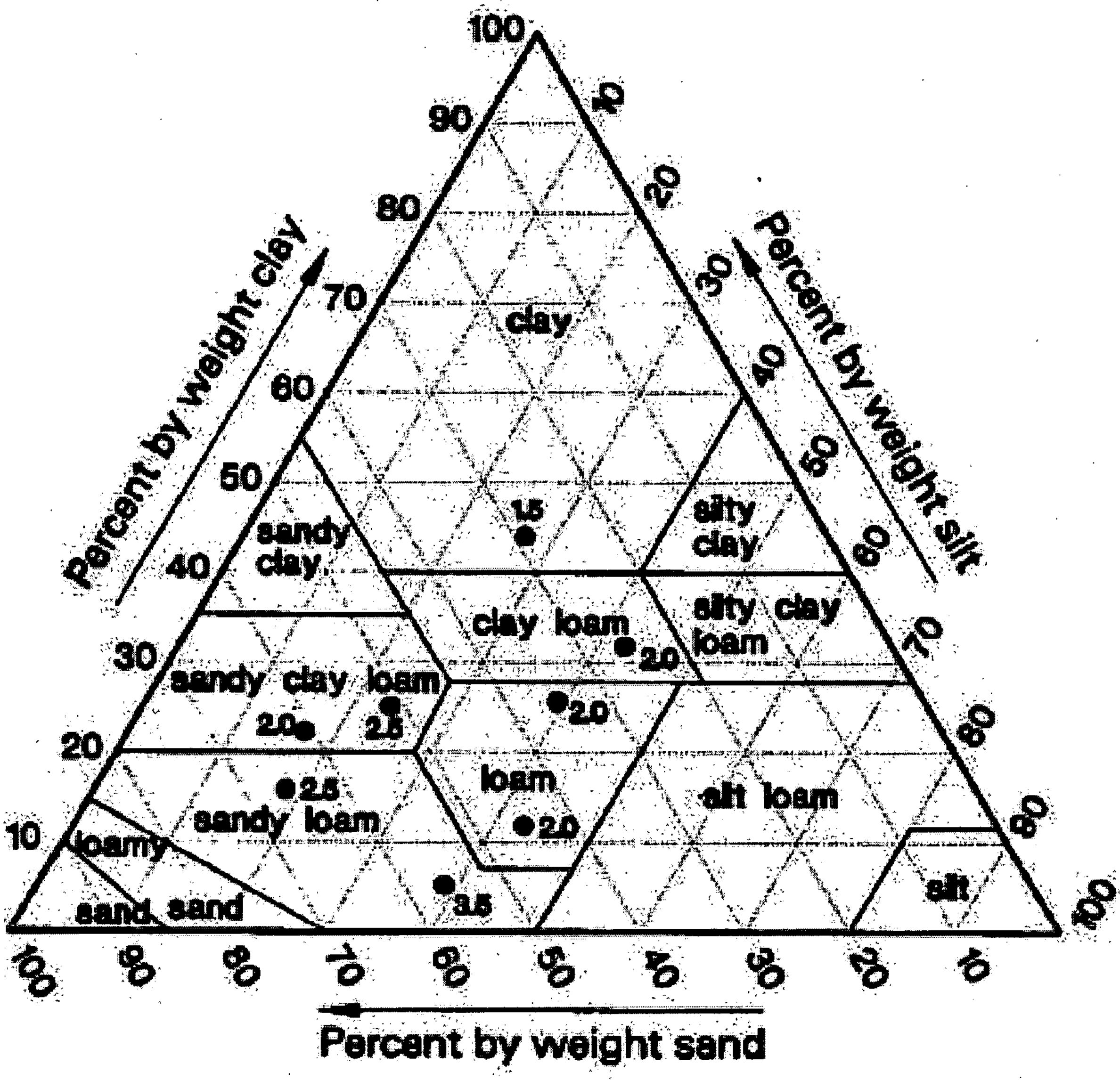
Data from Stapleton Airport will not reflect known differences in wind speed and the decrease in solar radiation due to Rocky Flats proximity to the mountains. Both of these factors affect the water balance calculated by UNSAT-H. The stronger winds found at Rocky Flats will increase evaporation and transpiration. Reduced solar radiation in late afternoons will reduce evaporation and transpiration. Both wind speed and solar radiation interact with slope aspect. The decrease in solar radiation due to the mountains will be smaller than differences seen between natural or engineered north and south slopes. The west-facing slopes that may be most affected by reduced evening solar radiation will receive the largest 'benefit' of increased drying from down-canyon winds.

A small reduction on the order of 1 percent in solar radiation will also occur at RFETS due to the mountains in the west. The average day length is slightly greater than 12 hours. The inclination of the mountains to the west is about 4 degrees above the horizon. Thus, approximately 4/180 or about 2 percent of the 12 hours of sunlight is blocked. Because of the lower intensity of evening radiation, however, less than 2 percent of solar radiation is blocked. Because RFETS itself is on an overall eastern incline, part of the solar radiation loss is compensated for by 'extra' morning radiation.

Adequate climate data have not been maintained at Rocky Flats, and there are only 3 years of data available. A comparison of the available data to the Boulder, Colorado Springs, and Stapleton data indicate that the three sites are remarkably similar in climate, showing essentially local variations in a semi-arid climate. Performance differences based upon climatic variations are expected to be small.

C.3.2 Soils

All three sites being evaluated have a range of soil properties. Rocky Mountain Arsenal showed a range of available soil types from clay to loam to sandy loam as shown in Figure C-5. Figure C-5 also shows the minimum calculated alternative cover thickness required for a given soil type at RMA. For example, 2.5 means a minimum of 2.5 feet of soil of the indicated texture would be required to control percolation. These depths do not reflect any additional erosion protection requirement. Fort Carson evaluated the Fort Collins series soil, which is a loamy mixture of



Source: Chadwick et al. 1999

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Range of Available Soil Types at Rocky Mountain Arsenal

Figure C-5

S:\Projects\9373\Drawings\Figures_4-15-02\Landfill\Appendix_C\Figure_C-5_lf.cdr alluvial and wind deposited materials. At Rocky Flats, off-site borrow sources were tested and categorized as sandy loam. This soil is similar to the soils used at the other two locations and is suitable for use in an alternative cover. However, RFETS has yet to select a final source of borrow material for the proposed cover on the Present Landfill. Although large volumes of suitable material appear available either on-site or at nearby, off-site commercial sources, the material to used will need to be characterized and the design profile reevaluated numerically during the design phase of the project.

C.3.3 Vegetation

Cool season plants such as native western wheatgrass, green needle grass, and forbs, which are present in all three locations, green up in early spring and rapidly transpire water accumulated in the soil profile during winter. Warm season plants, such as native grama and bluestem grasses, also present at all three locations, transpire more effectively than cool season grasses during the warm summer months.

Typical native vegetation on the soils at the Fort Carson alternative cover site (Fort Collins soil series, http://www.statlab.iastate.edu/cgi-bin/osd/osdname.cgi) is blue grama, western wheat grass, buffalo grass, side-oats grama, and sand dropseed. This vegetation is common across the southern Great Plains and reflects the seed mixes used at both Rocky Flats and Rocky Mountain Arsenal.

Native prairies at mid-latitudes such as found in Colorado always have a mixture of both warm and cool season vegetation. The balance between these vegetation types at a given location is dynamic. Cool winters and dry summers result in a larger fraction of cool season vegetation cover. The dynamic will also be affected by microclimates such as north- or south-facing slopes. Inspection of the three sites shows very similar vegetation. Similar vegetation was also observed in evaluation of an alternative cover at Cheyenne, WY and the consistency in plant species composition is well-documented in soil surveys along the Front Range. The mixture of plants with varying rooting strategies and depths is a common theme at these three sites.

More details on the vegetation plan for the Present Landfill ET cover are provided in Section 4 of the Conceptual Design Report. Cool season grasses typically have a more fibrous root system while warm season grasses are more deeply rooted. However, rooting depths and distribution data should be interpreted carefully because root systems are dynamic and root water uptake occurs where the water is available. The common advice to water lawns more deeply and less frequently to encourage deeper rooting also applies to variations in rooting patterns caused by changes in rainfall patterns. Available numerical models are not proficient in tracking changes in rooting profiles. However, agronomic evaluation of cover performance generally supports numerical evaluations.

C.3.4 Regional Agronomic Work

From an agronomic perspective, an evapotranspirative cover makes ecological sense. In Colorado, fine and medium textured soils can hold the summer rains until evaporation and transpiration can remove the water. Typically, prairies or unwatered lawns in Colorado use up all plant available water and go brown after the peak rainfall months have passed and only green up during fall rains. The numerical models that indicate plant available water is depleted during the growing season indicate recharge is unlikely during the growing season because plants can use all available water. Therefore, percolation failure in landfill covers is more likely to be caused by winter precipitation when transpiration is low. Accordingly, parameter values in numerical models for plant cover and roots may not be that important in semi-arid settings as long as the plants can dry the soil out by the end of the growing season and the soil profile is dry going into the winter season.

More formal agronomic work northeast of Denver at the Central Plains Experimental Range by Sala et al. (1992) showed no percolation in a pan lysimeter below 135 centimeters (cm) over a 33-year period. This lysimeter is essentially an agronomic analogue of the RMA lysimeters focused more on rangeland productivity than on water balance components. The key vegetation design requirement is that available soil water should be fully used by the plant community during the growing season. The key soil requirement is that enough soil-water storage must be available to store precipitation while plants are dormant (approximately October to March).

C.4 Regulatory Requirements in the Western U.S.

Alternative cover performance standards and requirements vary greatly across the western U.S. California standards for equivalence are site-specific and allow up to 1 inch per year (inch/yr) percolation. Utah will soon permit a site where equivalent performance allows up to 8 centimeters of percolation as compared to a conventional soil cover. New Mexico defines equivalent covers as those that are within an order of magnitude of the percolation of the conventional cap at the low percolation values often obtained (often 0.01 inch/yr or less). Arizona sites can meet the equivalence criterion by showing upward flux from numerical models. Nebraska will soon examine existing local ACAP data from Omaha and likely make a decision to approve a nearby alternative cover based upon qualitative evaluation of the data.

C.5 Conclusions and Recommendations

Long-term agronomic studies and work done by the UMTRA program show that vegetated soils can effectively control percolation. Newer and ongoing studies by ALCD and ACAP are supporting these general conclusions. Colorado data from the climatically and ecologically similar Fort Carson and RMA and in-state agronomic data provide local support for these conclusions at RFETS.

Numerical models, such as UNSAT-H, are now used for design of alternative evapotranspirative covers in many western states. Many sites are proceeding with design of alternative covers without use of large ACAP-like pan lysimeters because of the accumulating performance data, high costs, and long time frames associated with extensive testing at relatively small sites.

From climatic, ecological, and soils perspectives, RFETS is similar to Fort Carson and RMA. Therefore, similar alternative cover performance would be expected at the RFETS site.

From a technical perspective, monitoring of the final cover makes more sense than inferring final cover performance from a nearby test plot. Test plots provide only an indication that a vegetated cover is likely to be suitable. Test plots cannot capture all the performance information provided through direct monitoring of the final cover such as the effects of methane in the Present Landfill on cover performance.

After appropriate numerical evaluation of alternative covers, RFETS should design, build, and monitor final covers without accompanying test plots. Monitoring of the deployed cover provides direct, and generally more conservative, information on cover performance.

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Attachment C1

Alternative Cover Project Summaries

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Rio Rancho Landfill, New Mexico

Location:	Rio Rancho, New Mexico
Owner:	Waste Management, Inc.
Closure Date:	Operating landfill. Final cover construction in three phases from 1998 to 2000.
Regulatory Contact/ Contact Information:	Mr. Edward J. Hansen, Solid Waste Bureau, New Mexico Environment Department, 1190 St. Francis Drive, Santa Fe, New Mexico, 87501, (505) 827-2328.
Site Contact/ Contact Information:	Mr. Jim Jordan, P.E., Waste Management, Inc., P.O. Box 15700, Rio Rancho, New Mexico, 87174, (505) 892-2055.
Consultant Contact/ Contact Information:	Mr. Mark Miller, Daniel B. Stephens & Associates, Inc., 6020 Academy NE, Suite 100, Albuquerque, New Mexico, 87109, (505) 822-9400.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard synthetic barrier design must be demonstrated following the NMED HELP modeling Guidance Document.
Alternative Cover Profile:	Two ET cover design alternatives are approved based upon the permeability of the borrow soil: 30 inches of 7.2×10^{-4} cm/sec soil or 42-inches of 1.5×10^{-3} cm/sec soil; each covered by an additional 6-inch topsoil layer.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	None.
Results to Date:	None.

Los Lunas Landfill, New Mexico

Location:	Los Lunas, New Mexico
Owner:	Village of Los Lunas, New Mexico
Closure Date:	1977
Regulatory Contact/ Contact Information:	Mr. Edward J. Hansen, Solid Waste Bureau, New Mexico Environment Department, 1190 St. Francis Drive, Santa Fe, New Mexico, 87501, (505) 827-2328.
Site Contact/ Contact Information:	Ms. Betty Behrend, Utilities Director, Village of Los Lunas, P.O. Box 1209, Los Lunas, New Mexico, 87031, (505) 865-1377.
Consultant Contact/ Contact Information:	Mr. Mark Miller, Daniel B. Stephens & Associates, Inc., 6020 Academy NE, Suite 100, Albuquerque, New Mexico, 87109, (505) 822-9400.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard design must be demonstrated following the NMED HELP modeling Guidance Document. ET cover alternative design compared to the standard design for an unlined landfill consisting of 18 inches of 10^{-5} cm/sec soil with a 6-inch topsoil layer.
Alternative Cover Profile:	ET cover design consists of 24 inches of 1×10^{-4} cm/sec on-site soil.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	None.
Results to Date:	None.

Hobbs Landfill, New Mexico

Location:	Hobbs, New Mexico
Owner:	Waste Management, Inc.
Closure Date:	2000
Regulatory Contact/ Contact Information:	Mr. Edward J. Hansen, Solid Waste Bureau, New Mexico Environment Department, 1190 St. Francis Drive, Santa Fe, New Mexico, 87501, (505) 827-2328.
Site Contact/ Contact Information:	Mr. Jim Jordan, P.E., Waste Management, Inc., P.O. Box 15700, Rio Rancho, New Mexico, 87174, (505) 892-2055.
Consultant Contact/ Contact Information:	Mr. Mark Miller, Daniel B. Stephens & Associates, Inc., 6020 Academy NE, Suite 100, Albuquerque, New Mexico, 87109, (505) 822-9400.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard design must be demonstrated following the NMED HELP modeling Guidance Document. ET cover alternative design compared to the standard design for an unlined landfill consisting of 18 inches of 10^{-5} cm/sec soil with a 6-inch topsoil layer.
Alternative Cover Profile:	ET cover design consists of 24 inches of 4.2×10^{-4} cm/sec on-site soil with an additional 6-inch topsoil layer.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	None.
Results to Date:	None.

Roswell Municipal Landfill, New Mexico

Location:	Roswell, New Mexico
Owner:	City of Roswell, New Mexico
Closure Date:	Operating landfill. Original 35-acre cell closed in 1998.
Regulatory Contact/ Contact Information:	Mr. Edward J. Hansen, Solid Waste Bureau, New Mexico Environment Department, 1190 St. Francis Drive, Santa Fe, New Mexico, 87501, (505) 827-2328.
Site Contact/ Contact Information:	Ms. Betty Behrend, Utilities Director, Village of Los Lunas, P.O. Box 1209, Los Lunas, New Mexico, 87031, (505) 865-1377.
Consultant Contact/ Contact Information:	Mr. Mark Miller, Daniel B. Stephens & Associates, Inc., 6020 Academy NE, Suite 100, Albuquerque, New Mexico, 87109, (505) 822-9400.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard synthetic barrier design must be demonstrated following the NMED HELP modeling Guidance Document.
Alternative Cover Profile:	Alternative cover consists of GCL barrier layer overlain by a 24-inch thick soil rooting medium and a 6-inch topsoil layer.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	None.
Results to Date:	None.

Southwest Landfill, New Mexico

Location:	Albuquerque, New Mexico
Owner:	Southwest Landfill, Inc.
Closure Date:	Operating landfill. Cover design approved under permit.
Regulatory Contact/ Contact Information:	Mr. Edward J. Hansen, Solid Waste Bureau, New Mexico Environment Department, 1190 St. Francis Drive, Santa Fe, New Mexico, 87501, (505) 827-2328.
Site Contact/ Contact Information:	Mr. Rafael Valepena, General Manager, Southwest Landfill, 5816 Pajarito SW, Albuquerque, New Mexico, 87121, (505) 242-2020.
Consultant Contact/ Contact Information:	Mr. Mark Miller, Daniel B. Stephens & Associates, Inc., 6020 Academy NE, Suite 100, Albuquerque, New Mexico, 87109, (505) 822-9400.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard synthetic barrier design must be demonstrated following the NMED HELP modeling Guidance Document.
Alternative Cover Profile:	ET cover design consists of 36 inches of 10^{-4} cm/sec on-site soil with an additional 6-inch topsoil layer.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	None.
Results to Date:	None.

Glendale Landfill, Arizona

Location:	Glendale, Arizona
Owner:	City of Glendale
Closure Date:	Still Operating
Regulatory Contact/ Contact Information:	Dick Jefferies 602-207-4122
Site Contact/ Contact Information:	
Consultant Contact/ Contact Information:	Rust, and Craig Benson
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard synthetic barrier design must be demonstrated modeling using UNSAT-H.
Alternative Cover Profile:	Two ET cover design alternatives are being monitored. A single 5-ft thick layer of compacted silty sand and an 18 inch gravel capillary break in the middle of 3.5 ft of sand. There are four plots; each design is being tested with and without vegetation.
Test Pad Monitoring Required:	Yes
Final Cover Monitoring Required:	No
Monitoring Parameters:	
Results to Date:	

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Northwest Regional Landfill, Arizona

Location:	Surprise, Arizona
Owner:	Waste Management
Closure Date:	Still in operation
Regulatory Contact/ Contact Information:	
Site Contact/ Contact Information:	Jim Denson, Waste Management, (602) 757-3352
Consultant Contact/ Contact Information:	SCS Engineers 2019 North Avenue, Sheboygan, Wisconsin 53083, Rolland G. Boehm P.E.
Cover Performance Criteria:	Infiltration reduction performance equivalent to the standard synthetic barrier design must be demonstrated modeling using UNSAT-H.
Alternative Cover Profile:	Single 4-foot thick monolithic soil layer constructed of silty sand.
Test Pad Monitoring Required:	No
Final Cover Monitoring Required:	No
Monitoring Parameters:	
Results to Date:	

City of Cheyenne Sanitary Landfill, Wyoming

Location:	Cheyenne, Wyoming
Owner:	City of Cheyenne
Closure Date:	Approximately 2009.
Regulatory Contact/ Contact Information:	Bob Doctor, WDEQ, Caspar, Wyoming (307) 473-3450.
Site Contact/ Contact Information:	Kevin Sherrodd, Assistant City Engineer, (307) 637-6264.
Consultant Contact/ Contact Information:	Clay Muirhead, Terracon, Cheyenne, Wyoming, (307) 632-9224.
Cover Performance Criteria:	Evaluation will be based upon HELP modeling results as compared to a prescriptive cover standard. The existing liner varies by cell. Some cells are unlined, some with GCL and some with a PVC liner over two feet of local clay. The unlined component of the landfill only requires a 10^{-5} cm/s soil cover.
Alternative Cover Profile:	In process.
Test Pad Monitoring Required:	Not yet determined.
Final Cover Monitoring Required:	The state will probably require monitoring with an alternative which is not typically required on standard covers.
Monitoring Parameters:	Groundwater monitoring, methane monitoring
Results to Date:	No data. No alternative cover has yet been approved at this site.

Rocky Mountain Arsenal, Colorado

Location:	Commerce City, Colorado
Owner:	U.S. Army, Shell
Closure Date:	Various. Army Trenches, Shell Trenches, and South Plants will all require similar covers.
Regulatory Contact/ Contact Information:	Susan Chaki, (303) 692-3341.
Site Contact/ Contact Information:	Lou Greer, (303) 853-3951.
Consultant Contact/ Contact Information:	Mark Ankeny, (505) 822-9400.
Cover Performance Criteria:	The criteria for failure of the ET cover is 1.3 mm/yr flux through the ET cover and was based upon German landfill data available at the time.
Alternative Cover Profile:	42", 48", and 60" of local topsoil are being tested.
Test Pad Monitoring Required:	Yes. Pan lysimeter configuration.
Final Cover Monitoring Required:	Yes. Monitoring requirements are not yet finalized.
Monitoring Parameters:	Monitoring Parameters. Water content at six depths in each profile. Runoff. Percolation as measured by a tipping buck rain gauge and catchment.
Results to Date:	Covers are performing adequately.

Fort Carson, Colorado

Location:	Colorado Springs, Colorado
Owner:	U.S. Army
Closure Date:	Various. Fort Carson has numerous landfills at their site; three of these have been selected for closure with ET covers. Landfill #5 is approximately 20 acres in size, a World War II landfill, and operated 1942 through 1956. The Army opted not to characterize it and categorized it as a hazardous waste landfill.
Regulatory Contact/ Contact Information:	Harlen Ainscough, (303) 692-3337.
Site Contact/ Contact Information:	James Henderson, EEQ1, Fort Carson, Colorado, (719) 526-8001.
Consultant Contact/ Contact Information:	John England, Earth Tech, (303) 804-2350.
Cover Performance Criteria:	The criteria for failure of the ET cover assumed all failure indicated by each monitoring device at each cluster which would trigger additional monitoring. A simple "failure" of an individual monitoring point merely is an alert and may require further evaluation.
Alternative Cover Profile:	Four feet of local topsoil.
Test Pad Monitoring Required:	No. The rationale for not needing ET Test pads was as follows: (1) RMA was doing extensive testing which was sufficient to prove the concept, (2) the nature of the material being covered is solid waste and less problematic than RMA waste, and (3) Ft. Carson operation had used unusually large amounts of soil for daily cover.
Final Cover Monitoring Required:	Monitoring Parameters. Monitoring of the ET cover includes four clusters of instrumentation: (1) thermocouple psychrometers, (2) neutron probe access tubes, and (3) lysimeters.
Monitoring Parameters:	Not applicable.
Results to Date:	Cover appears to be performing adequately.

American Ecology Hazardous Waste and Treatment Disposal Facility, Idaho

Location:	Grand View, Southwest Idaho (http://www.americanecology.com/chemical_grandview.htm)
Owner:	American Ecology
Closure Date:	Ongoing. Individual cells closed in 1999.
Regulatory Contact/ Contact Information:	Brian Gaber, (208) 373-0502.
Site Contact/ Contact Information:	Simon Bell, (208) 834-2275, ext. 3036.
Consultant Contact/ Contact Information:	Mark Ankeny, (505) 822-9400, ext. 118.
Cover Performance Criteria:	10^{-8} cm/s (3.2 mm/yr). Upcoming closures are likely to be permitted with higher flux standards.
Alternative Cover Profile:	Four feet of local silty soil.
Test Pad Monitoring Required:	Yes.
Final Cover Monitoring Required:	No.
Monitoring Parameters:	Two nests of instrumentation with water potentials, temperature profiles, calculated water fluxes, and bromide tracer test.
Results to Date:	Test cover is not fully vegetated. Fluxes have been below the standard so far.

Good Samaritan Village Landfill or Hastings South Landfill (Superfund site), Nebraska

Location:	Hastings, Nebraska
Owner:	Naval Ammunition Depot, City of Hastings, and others
Closure Date:	Has not been accepting waste for years.
Regulatory Contact/ Contact Information:	Gerald Gibson, Nebraska Department of Environmental Quality, (402) 471-4210.
Site Contact/ Contact Information:	David Wacker, City Engineer, Hastings, Nebraska, (402) 461-2308.
Consultant Contact/ Contact Information:	Jack Kretzmeyer, Arcadis, Geraghty & Miller, 35 E. Wacker Drive, Suite 1000, Chicago, 60601, (312) 263-6703.
Cover Performance Criteria:	A new cover will be required. The city prefers an alternative cover. NDEQ and the city are waiting for ACAP results from the (Omaha) Douglas County Landfill (Gerald Gibson or Mark Ankeny contact). If ACAP results look reasonable (no numerical standard has been set) then the probable resolution (according to NDEQ) will be to use a soil cover twice as thick as that found to be a suitable minimum for the Douglas County Landfill.
Alternative Cover Profile:	The cover will probably on the order of 5 feet thick of silty clay material.
Test Pad Monitoring Required:	ACAP results likely to be used in lieu of test pads.
Final Cover Monitoring Required:	Probably no cover monitoring requirements.
Monitoring Parameters:	None for the cover beyond regular inspections.
Results to Date:	None.

Millikan Landfill, California

Location:	San Bernadino County, California, 175 acre site. Eastern unit is a 22-acre alternative cover site.
Owner:	San Bernadino County Waste Management Division
Closure Date:	1997.
Regulatory Contact/ Contact Information:	Dixie Lass, (909) 782-4130.
Site Contact/ Contact Information:	Arthur L. Rivera, (909) 386-8775.
Consultant Contact/ Contact Information:	Gary Lass, (909) 860-3448.
Cover Performance Criteria:	Either 0.1 inch or 0.4 inches per year.
Alternative Cover Profile:	4 feet monofill over 2 feet of foundation soil.
Test Pad Monitoring Required:	No.
Final Cover Monitoring Required:	Yes. Four lysimeters on various slopes drain into tipping bucket rain gauges.
Monitoring Parameters:	Eight monitored soil water content profiles, 4 lysimeters, and 3 weather stations. The lysimeters are on sideslopes and 75 to 100 feet long, 30 inches wide and drain into a tipping bucket rain gauge.
Results to Date:	During rains, flows out of lysimeters up to 1^{-5} cm/s have occurred in El Niño years and during ponding on an intermediate deck. Total annual flux varied from none to 1 inch depending upon slope aspect and year.

Appendix D

Model Selection Report

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Model Recommendations for Conceptual Design of an Evapotranspiration Cover at the Rocky Flats Environmental Technology Site

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Appendix D.

Model Recommendations for Conceptual Design of an Evapotranspiration Cover at the Rocky Flats Environmental Technology Site

Daniel B. Stephens & Associates, Inc. (DBS&A) was contracted by Kaiser-Hill, LLC to perform modeling, conceptual design, and related activities for an evapotranspiration cover at Rocky Flats Environmental Technology Site (RFETS) for the Present Landfill. This report presents recommendations regarding the model to be used to design an evapotranspiration soil cover.

Numerical modeling is an important tool for design of evapotranspiration covers; however all numerical models have intrinsic limitations. A publication on groundwater models developed by Water Science and Technology Board, the Committee on Ground Water Modeling Assessment, and other organizations, extensively reviewed the accuracy of numerical models and the degree to which regulatory decisions could be based upon a modeled prediction of cover performance (Schwartz et al., 1990). This publication pointed out that the models often appear more certain and quantitative than they really are and that numerical models are a simplified mathematical conception of reality. The report also emphasized the value of carefully linking data collection with modeling needs and activities.

A review of landfill models conducted by Nixon et al. (1997) did not evaluate all the codes discussed in this report but found that no two models gave the same assessment, no model has been validated for long-term modeling performance, but that many models could be of potential use in assessment of landfill cover performance.

The primary objective of modeling the Present Landfill is to evaluate the potential for water movement through the cover into the underlying waste at the present landfill.

RFCA Attachment 10 identifies performance standards for these facilities. The basic minimum closure requirements are: (1) attainment of alternate concentration limits (ACLs) at the downgradient point of compliance (POC) for each facility and (2) generally declining contaminant levels over time. According to RFCA, the ACLs and POCs must be specified in the appropriate decision document and submitted for public review and regulatory approval.

Based upon RFCA Attachment 10 performance standards, the performance of the Present Landfill will depend upon a combination of cover performance and groundwater control measures. At this time, no specific RFETS cover performance requirements exists. However, the system as a whole must meet RFCA standards and cover performance is a major part of the system.

Because cover performance is critical to system performance, a model that can accurately predict the water balance of various cover alternatives is needed. If existing groundwater controls remain unchanged, cover performance will need to be improved. With improved groundwater controls, it is possible that the thin existing cover may be adequate from the RFCA performance standard discussed above. However, KH will design the cover with long term performance and appropriate allowances for long term erosion in mind. Thus, cover and groundwater results will be considered jointly to evaluate whether regulatory intent is satisfied.

Specific technical requirements for a landfill cover water budget model at RFETS are utilization of site specific vegetation, soil, and climate data. Basic vegetation data and specifications have already been compiled by RFETS and a similar effort was completed by Rocky Mountain Arsenal in 1995. Appropriate soils data to support these models are now being collected. Climate data are available from the airport through the National Climate Center. All models reviewed take into account properties of the material being covered.

Based on the evaluations of Schwartz et al. (1990) and Nixon et al. (1997) as well as the professional experience of the scientists and engineers at RFETS and DBS&A, five models were reviewed for use in the conceptual design project. The following sections present a discussion of HELP, HYDRUS-2D, EPIC, SoilCover, and UNSAT-H and their advantages and disadvantages for this project.

D.1 Summary

The unsaturated models HELP, HYDRUS-2D, EPIC, SoilCover, and UNSAT-H were reviewed for design of a landfill cover for the Present Landfill. Each of the models has strengths and weaknesses for landfill applications in general and for RFETS modeling, in particular. Specific attributes of the reviewed models are specified in Table D-1. Slopes, topography, and runoff are considered in two dimensions in HYDRUS-2D and are greatly simplified in the other four codes. In HYDRUS-2D, any water that does not infiltrate immediately leaves the model and runoff is not correctly calculated. HELP and EPIC use an SCS curve number to partition runoff. Hydrology is only considered in the five models for explicit modeling of the water balance of the evapotranspiration cover.

UNSAT-H is considered to be best for this application for the following reasons: (1) it is a physically based model that accurately describes water movement and redistribution in unsaturated soils systems such as landfill covers, (2) it has been successfully used at nearby Rocky Mountain Arsenal and Fort Carson, (3) intricacies of the model are well understood by consultants and regulators involved in the project, and (4) results from previous modeling exercises have been accepted by the Colorado Department of Public Health and Environment (CDPHE). UNSAT-H has also been widely used on many alternative cover projects in recent years and has been the primary model used to design landfill covers in the EPA Alternative Cover Assessment Program (http://www.dri.edu/Projects/EPA/boston-brochure2.html).

D.2 The HELP Model

The Hydrologic Evaluation of Landfill Performance (HELP) model was developed by Paul Schroeder and uses code extracted from other models including CREAMS (Chemical, Runoff, and Erosion from Agricultural Management Systems), HSSWDS (Hydrologic Simulation of Solid Waste Disposal Sites), and SWRRB (Simulation for Water Resources in Rural Basins). The HELP model is a user-friendly computer program that computes estimates of water balances for municipal landfills, RCRA and CERCLA facilities, and other land disposal systems (Schroeder, 1998). The model, a user's guide, and a documentation report are available online at http://www.wes.army.mil/el/elmodels/index.html. The current version is 3.07.

Table D1. Attributes of Reviewed Models
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Specific Parameter/ Attribute	EPIC	HELP	HYDRUS-2D	UNSAT-H	Soil Cover
Time step	Day	Day/Month/Year	Any	Any	Any
Physical properties					
Soil texture	I	I	I		I
Bulk density	I	I			
Maximum no. of soil layers	10	20	Any	Any	8
Percent organic matter	I				
Effective porosity	C				
SCS/runoff curve no.	I	I			
Soil albedo/net radiation	I			I	I
Topography/slope	I	I	I		
Site elevation	I			I	I
Initial soil temperature				I	I
Maximum ponding depth					
Land area	I	I	C		
Hydraulic properties					
Wilting point	I	I			I
Field capacity	I	I			
θ(h) function parameter			Y	Y	Y
Saturated water	C	I	I	I	I
Content/porosity					
Ks	I	I	I	I	I
Kh			C	C	
Depth to aquifer	I		I		I
Initial water content/head	I	C, I	I	I	I
Plant properties					
Potential transpiration	C	C	I	I	C
Evaporative depth	I	I			
Growing season length	C	C		I	I
Leaf area index	I	I		I	I
Left size/plant size and orientation	C				
Root density	C			I	I
Root depth	I		I	I	I
Canopy albedo				I	C
Vegetative index	I				
Climatological					
Precipitation time scale	M	D	Any	D, H	Any

Table D1. Attributes of Reviewed Models

Specific Parameter/ Attribute	EPIC	HELP	HYDRUS-2D	UNSAT-H	Soil Cover
Precipitation maximum event		Y			I
Potential evaporation	C		I	I	I
Relative humidity	M	Y			C
Snow density and depth		C			I
Air temperature daily maximum/minimum	C	C		I	I
Temperature time scale	M	D		D	D
Solar radiation	M	Y		D	D
Cloud cover				D	
Wind speed	M	Y		D	D
Latitude/longitude	I	C			I

I = Property input
C = Property computed
Y = Year

M = Month
D = Day
H = Hour

The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model is sufficiently sophisticated to consider all of the principal design parameters including vegetation, soil types, geosynthetic materials, initial moisture conditions, layer thickness, slopes, drain spacing, and climate.

The model accepts weather, soil, and design data and uses solution techniques that account for the effects of surface storage, snowmelt, frozen soil, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and lower boundary leakage through soil, geomembrane, or composite liners.

The HELP model has a default evapotranspiration database for 183 U.S. cities, including Denver, containing data for latitude, evaporative zone depths, leaf area indices, growing season, average wind speed, and average quarterly relative humidities. A default precipitation database is included, containing 5 years of daily values for 102 cities throughout the United States, including Denver. The model also includes an algorithm that generates synthetic weather data for daily precipitation, temperature, and solar radiation. Weather data can also be imported in standard NOAA weather station format.

Soil data requirements include porosity, field capacity, wilting point, initial moisture content, and saturated hydraulic conductivity are required inputs. Runoff curve numbers must also be selected and can be entered by the user or calculated by the model based on site-specific data.

Landfill systems, including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners, may be modeled. The program facilitates rapid estimation of the daily, monthly, annual, and average annual amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may result from the operation of a wide variety of landfill designs. The model applies to open, partially closed, and fully closed sites and serves designers and permit writers.

The model's advantages and disadvantages are as follows:

- The model is user friendly, unusually easy to run, simple to learn for most users, and sanctioned for use by the U.S. EPA.

- The model does an effective job of integrating the major components of the water balance into a useable model.

- The model does not take a physically based approach to water movement in the soil and is considered by most experts to yield unduly conservative estimates of percolation in arid and semiarid applications.

While other models may yield a superior estimate of percolation through a vegetated cover, this model is still very useful for such design purposes as slope performance evaluation or drain spacing.

D.3 The HYDRUS-2D Model

The HYDRUS-2D program is a Microsoft Windows-based shell that uses the finite element model SWS_2D to simulate movement of water, heat, and multiple solutes in variably saturated media. The program numerically solves the Richards' equation for saturated and unsaturated water flow, and the Fickian-based advection-dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equation considers conduction as well as convection with flowing water. The solute transport equations consider advective-dispersive transport in the liquid phase and diffusion in the gaseous phase. The program is used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. More detailed information on the model can be found at http://www.ussl.ars.usda.gov/MODELS/HYDRUS2D.HTM.

The unsaturated soil hydraulic properties are described using van Genuchten (1980), Brooks and Corey (1964), and modified van Genuchten type analytical functions. Modifications were made to improve the description of hydraulic properties near saturation. The HYDRUS-2D code incorporates hysteresis by using an empirical model that assumes that drying scanning curves are scaled from the main drying curve, and wetting scanning curves from the main wetting curve. HYDRUS-2D also implements a scaling procedure to approximate hydraulic variability in a given soil profile by means of a set of linear scaling transformations which relate the individual soil hydraulic characteristics to those of a reference soil.

The model's advantages and disadvantages are as follows:

- The physics and mathematics of unsaturated flow are better captured in this model than in any other available model.
- HYDRUS-2D is the only model capable of accurately modeling lateral flow in a landfill cover.
- The model is also the best suited of those examined for evaluation of runoff/runon systems.
- The model assumes that any precipitation that does not infiltrate disappears from the system and does not appear as runon elsewhere.
- Although HYDRUS-2D is being modified in the summer of 2001 to better account for transpiration, it has not focussed on vegetative parameters and has not been validated for a landfill cover analogue.

Because of the importance of transpiration in an evapotranspirative cover, this model is less useful than a one-dimensional model that more carefully accounts for transpiration in the water balance.

D.4 The EPIC Model

The Environmental Policy Integrated Climate (EPIC) model was developed as an erosion predictor and as an agricultural water balance tool. The major components in EPIC are weather simulation, hydrology, wind and water erosion sedimentation, wind damage, nutrient cycling, pest damage, pesticide fate, plant growth, plant growth response to global warming, soil

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temperature, tillage, economics, and plant environment control. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, pesticides, and sediment. Detailed information about this model can be obtained on the Internet at EPIC On Line (http://www.brc. tamus.edu/epic/).

Runoff is calculated using a modified SCS curve number technique. Water storage in soil uses a 'bucket method' based upon hydraulic conductivity, field capacity, and wilting point. Water drains from a soil layer when field capacity is exceeded and stops when water content returns to field capacity. Potential evapotranspiration can be estimated by Penman or Penman-Monteith equations or by two simplified methods used where fewer climate data are available. Actual evaporation is estimated based upon soil depth and water content. Actual transpiration is calculated as a linear function of potential evaporation and leaf area index.

Of the codes examined in this report, EPIC most rigorously defines plant growth parameters. While the model includes a number of agricultural modules irrelevant to landfill concerns (e.g., fertilization, grazing, pesticide applications), these do not affect the potential utility of the model for landfill applications. Because plant transpiration is an import component of the water balance in an evapotranspirative cover, reasonable evaluation of plant transpiration can be made by this more complex model. However, much of the plant data are not easily available for many of the native species likely to be used in the Present Landfill cover. Estimation of these parameters will reduce the potential accuracy of the model.

Individual components of the relatively complex EPIC model have been validated at various locations. Hauser and Shaw (1994) have validated portions of the model and reviewed other validation efforts.

The model's advantages and disadvantages are as follows:

- The model does a fairly good job with the overall water balance and, similar to HELP, uses a 'bucket model' to simplify water flow and redistribution in a soil cover. As such, it has some of the same strengths and weaknesses.

It is useful for a better look at the overall components of the water balance but is likely to provide less information on the dynamics of water storage and movement in a landfill cover.

D.5 The Soil Cover Model

SoilCover is a fully coupled heat and mass transfer finite element model used to simulate the one-dimensional flow of water, vapor, and heat in soils. A modified form of the Penman equation is used to predict evaporation. The program input and output is done from within Microsoft and all features of Excel are available to the modeler. The finite element solver is a Fortran executable file that is called from within Excel. The model can estimate the effects of freezing on the water balance and can simultaneously estimate effects of thermal water movement and transpiration. The model has less flexibility in selection of unsaturated hydraulic functions than UNSAT-H or HYDRUS-2D. Transpiration is estimated based upon leaf area index. A detailed description of the software is available on the Internet at http://www.vadose-science.com/page7.html.

An excellent feature of the model is user customizable on-screen graphics during program execution showing continuous plots of daily and cumulative actual surface and internal fluxes, water balance, saturation, or temperature profiles. For a new user, the learning curve is less steep than any of the alternative codes evaluated except for HELP.

Input requirements include soil properties (including the soil water characteristic curve and saturated hydraulic conductivity); a full set of climate parameters including rainfall, radiation, relative humidity and wind speed; and vegetation parameters including leaf area index, and rooting depth; boundary conditions, initial conditions, and modeling details.

The model's advantages and disadvantages are as follows:

- The model is relatively easy to use and automatically generates much of the desired graphical outputs.

- There is less flexibility in selection of the lower boundary conditions, which may be an important issue in some modeling scenarios.

- The model uses several functions from Canadian literature that are less familiar to many U.S. consultants and permit writers.

- Relatively little validation work appears available in the literature for this newer model.

Overall, this model is probably second choice for use at RFETS.

D.6 The UNSAT-H Model

UNSAT-H is a FORTRAN computer code used to simulate the one-dimensional flow of water, vapor, and heat in soils. The code addresses the processes of precipitation, evaporation, plant transpiration, storage, and deep drainage. The model has been verified against analytical solutions and validated against lysimeter data by Fayer et al. (1992). More information about UNSAT-H is available on the Internet at http://etd.pnl.gov:2080/~mj_fayer/unsath.htm.

Runoff is not explicitly calculated and a runoff value is inferred in the model when rainfall intensity exceeds the soil infiltration rate. While vapor flux can be calculated, it cannot be calculated when transpiration is being used in the model. Thus, for normal evapotranspiration covers, UNSAT-H ignores water vapor movement. Evaporation is driven by weather data through the use of the Penman equation. Transpiration is based upon the Ritchie equation, which drives transpiration as a function of leaf area index. Transpiration is also dependent upon rooting distribution in the soil profile and upon soil water potential.

UNSAT-H was thoroughly evaluated for modeling alternative landfill cover performance at nearby Rocky Mountain Arsenal and was also used for design of a large ongoing lysimeter study at the same site. RFETS has similar climate, soils, and vegetation. CDPHE regulators have required UNSAT-H modeling at other sites (Fort Carson) and are more familiar with this model than the alternatives. In informal discussion, the regulators have discussed making UNSAT-H the standard model required to establish design performance.

The model's advantages and disadvantages are as follows:

- UNSAT-H is the most commonly used model that takes a physically based modeling approach to water movement in soil and has been successfully validated using water balance studies at Hanford.
- It is a physically based model that accurately describes water movement and redistribution in unsaturated soils systems such as landfill covers.
- It has been successfully used at nearby Rocky Mountain Arsenal.
- Intricacies of the model are well understood by consultants.
- Results from previous modeling exercises have been accepted by the CDHE.
- The model does only a fair job of estimating runoff and does not allow vegetation to respond to weather.

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Appendix E

Landfill Gas Generation Report

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Assessment of Landfill Gas Generation at the Present Landfill Rocky Flats Environmental Technology Site

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Appendix E.

Assessment of Landfill Gas Generation at the Present Landfill Rocky Flats Environmental Technology Site

This report presents an assessment of landfill gas (LFG) generation for the Present Landfill at the Rocky Flats Environmental Technology Site (RFETS). Daniel B. Stephens & Associates, Inc. (DBS&A) was contracted by Kaiser-Hill, LLC to perform modeling and conceptual design for an evapotranspiration (ET) cover for the Present Landfill. This report includes calculations of the LFG generation rate and presents the cover design approach to address LFG.

ET covers will be evaluated to determine their suitability as a component of final closure of the Present Landfill. The ET cover conceptual design has numerous objectives, and LFG control is just one of the objectives that must be achieved. If ET covers are determined to be the most suitable design approach, then the ET cover designs will ultimately be incorporated into Decision Documents for final closure of the site.

The Present Landfill contains municipal and industrial solid waste, and has received some sludges and hazardous waste. The landfill was operated as municipal landfill, receiving waste from Rocky Flats facilities from 1968 through 1998. An interim soil cover has been place over the entire site and seeded to establish vegetation. Passive LFG vents have been installed in the interim cover.

LFG generation at the Present Landfill was evaluated with regard to impacts the ET cover may cause. The final cover design must consider effects of subsurface LFG migration and air emissions. The ET cover will allow LFG to passively vent; therefore, subsurface gas migration is not exacerbated by increasing LFG pressures. The diffuse venting of LFG through the ET cover soil can also provide a reduction in air emissions through oxidation of methane and biodegradation of hazardous air pollutants (HAPs).

The effects of LFG on cover vegetation were assessed based upon the expected gas flux through the cover. The effects of LFG on cover vegetation and rooting depth are important design considerations. If needed, design alternatives for a landfill gas venting layer are available to promote vegetation by reducing methane and increasing oxygen in the root zone. For low rates of LFG generation, cover vegetation is not adversely impacted and can achieve a sufficient rooting depth.

The assessment of landfill gas generation is presented in the following sections of this report:

- Landfill gas generation potential
- Cover impacts on LFG emissions and migration
- LFG impact on cover performance
- Regulatory overview and compliance
- LFG controls
- Conclusions and design recommendations

E.1 Introduction

Landfill gas is generated within a waste disposal site by the natural decomposition of the organic materials present. Methane (CH_4) and carbon dioxide (CO_2) are the primary constituents of landfill gas, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of CH_4 and CO_2 are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation, including rate and composition, proceeds through four phases. The first phase is aerobic (i.e., with oxygen [O_2] available) and the primary gas produced is CO_2. The second phase is characterized by O_2 depletion, resulting in an anaerobic environment, where large amounts of CO_2 and some hydrogen (H_2) are produced. In the third phase, CH_4 production begins, with an accompanying reduction in the amount of CO_2 produced. Nitrogen (N_2) content is initially high in landfill gas in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of CH_4, CO_2, and N_2 becomes fairly steady. The steady state mixture ratio of CH_4 to CO_2 is approximately 55 to 45 percent, respectively. The total time and phase duration of gas generation varies with landfill conditions (i.e., waste composition, design, management, and anaerobic state) (U.S. EPA, 1998).

Methane gas concentrations may be measured based upon two reporting scales: either as the percentage of methane as gas in air (percent GIA or simply "percent") or as percentage of the lower explosive limit (percent LEL). The LEL for methane is equivalent to 5 percent GIA. In this report, methane and other gas constituents are reported as percent GIA unless otherwise noted.

Typically, LFG gas also contains a small amount of non-methane organic compounds (NMOCs). This NMOC fraction often contains various HAPs, greenhouse gases (GHG), and compounds associated with stratospheric ozone depletion. The NMOC fraction also contains volatile organic compounds (VOC) (U.S. EPA, 1998).

E.2 Landfill Gas Generation Potential

Landfill gas generation potential depends on several factors such as: volume of waste in-place, waste composition (cellulose and lignin content), waste moisture content, waste pH, and waste carbon to nitrogen ratio. The most critical of the above listed factors are the volume of waste in-place, waste composition, and moisture content. The following sections describe conditions of the Present Landfill and how they relate to gas production as well as estimates of LFG generation at the Present Landfill.

E.2.1 In-Place Waste Volumes

In-place waste volumes are critical to the amount of LFG produced at a landfill. Naturally, the more material in-place the more LFG generation and subsequent emission. The Present Landfill has a relatively small amount of material in-place. The areal extent of the Present Landfill is 21 acres (ERM, 1994). Waste thickness varies between 1 and 40 feet, with the youngest and thickest waste deposit being in the eastern half of the landfill (ERM, 1994). The average total waste thickness appears to be between 15 to 20 feet with an average unsaturated waste thickness of 11 feet (ERM, 1994).

Based on Tables 2 and 3 of the Technical Memorandum dated October 5, 1994 the final projected waste in-place is approximately 403,561 cubic yards (308,585 cubic meters [m^3]) or 201,781 tons (183,020 megagrams [Mg]) based on an in-place waste density of 1,000 pounds per cubic yard (lbs/yd^3). It appears these estimates were based upon aerial photographs taken of the Present Landfill on three separate occasions. These aerial surveys were then compared to a base grade (cell floor) survey and the resulting volume was estimated. It was assumed that 25 percent of the total volume was cover soil, therefore it was subtracted out and the remaining volume was assumed to be waste compacted at an average density of 1,000 lbs/yd^3. From each aerial survey the resulting volume was divided by the total number of years that the waste was deposited to determine an average annual acceptance rate over the period. Waste acceptance rates for 1994 through 1997 were projected based on previous acceptance rates, the annual rates for this period have not been confirmed, but they appear to be an appropriate estimate. Table E-1 summarizes the volume and mass of material in-place at the Present Landfill.

E.2.2 Waste Composition and Conditions

Waste composition is a major component of total LFG generation volume and rate determinations. The two most important aspects of waste composition are how much LFG the waste will produce and when it will produce it. Waste composition is typically evaluated using the following five categories with corresponding theoretical methane yields (Emcon, 1980):

- *Rapidly degradable:* Food waste, leaves, grass (varies from 8.38 - 8.57 liters CH_4 per kilogram waste)
- *Moderately degradable:* Paper, textiles, wood (varies from 0.48 - 30.5 liters CH_4 per kilogram waste)
- *Slowly degradable:* Rubber, plastics, asphaltic metal, wall board (0.37 liters CH_4 per kilogram waste)
- *Inert/inorganic:* Glass, metals, concrete, soil (non-degradable)
- *Fines/unknown:* Typically unrecognizable, highly decomposed material and soil (non-degradable)

Table E-1. In-Place Waste Volume and Mass at the Present Landfill
Rocky Flats Environmental Technology Site

Year	Volume of Waste In-place (cubic yards)	Mass of Waste In-place (tons)	Mass of Waste In-place (megagrams)
1968	10,178	5,089	4,616
1969	10,178	5,089	4,616
1970	10,178	5,089	4,616
1971	10,178	5,089	4,616
1972	10,178	5,089	4,616
1973	10,178	5,089	4,616
1974	10,178	5,089	4,616
1975	10,000	5,000	4,535
1976	10,000	5,000	4,535
1977	10,000	5,000	4,535
1978	10,000	5,000	4,535
1979	10,000	5,000	4,535
1980	10,000	5,000	4,535
1981	10,000	5,000	4,535
1982	10,000	5,000	4,535
1983	10,000	5,000	4,535
1984	10,000	5,000	4,535
1985	10,000	5,000	4,535
1986	10,000	5,000	4,535
1987	28,125	14,063	12,755
1988	28,125	14,063	12,755
1989	28,031	14,016	12,712
1990	28,125	14,063	12,755
1991	28,125	14,063	12,755
1992	11,964	5,982	5,426
1993	11,964	5,982	5,426
1994	11,964	5,982	5,426
1995	11,964	5,982	5,426
1996	11,964	5,982	5,426
1997	11,964	5,982	5,426
Total	403,561	201,781	183,020

Typically, rapidly degradable waste will begin to decompose and generate gas shortly after being placed in the landfill. This type of waste will normally generate the majority of its gas within a few years, while moderately and slowly degradable waste will decompose over decades and centuries, respectively. Food waste and grass clippings tend to degrade the fastest because they have a high moisture content when they are placed in the landfill, whereas paper and textiles have a low moisture content and require additional moisture (i.e., precipitation or groundwater) in order to decompose.

In 1986 and 1987, approximately 1,500 waste streams were identified at RFETS, 338 of which were sent to the landfill for disposal. This included 241 waste streams identified as non-hazardous and 97 solid waste streams that contained hazardous waste or hazardous waste constituents. The non-hazardous waste streams include office trash, paper, rags, demolition materials, empty cans and containers, used filters, electrical components, dried sanitary sewage sludge, solid sump sludge, and other miscellaneous sludges. Hazardous waste streams were broken down into the following four categories (ERM, 1994):

- Containers partially filled with paint, solvents, degreasing agents, and foam polymers
- Wipes and rags contaminated with the above materials
- Paint and oil filters
- Metal cuttings and shavings, including mineral and asbestos dust and miscellaneous metal chips coated with hydraulic oil and carbon tetrachloride

After the fall of 1986, wastes with hazardous constituents were no longer placed in the landfill (ERM, 1994). Based on review of Table 4-4 in the Technical Memorandum (ERM, 1994), the majority of material disposed of at RFETS is moderately and slowly degradable material, with a notable amount of inert (non-degradable) material. Unlike typical municipal landfills, the Present Landfill does not contain as much putrescible waste, so it is not expected to generate as much gas as a conventional landfill.

E.2.3 Landfill and Waste Conditions

Conditions of the waste and landfill are also of vital importance to the generation of landfill gas. Moisture content of the waste is by far the most critical variable in the determination of LFG generation rate. Like the degradability categories listed in the previous section, moisture content also plays a vital role in determining how quickly waste will degrade, the more moisture the quicker the decomposition and therefore the more gas produced. Moisture content does not change the total amount of gas that can be produced, but it determines the rate and duration of gas generation.

Waste encountered during the Phase 1 methane survey in 1994 was commonly found to be moist (ERM, 1994). Municipal waste is typically an average moisture content of 25 percent when it is placed in a landfill. Higher moisture contents in the range of 60 to 80 percent favor maximum methane production (Emcon, 1980). Also, approximately 25 percent of the total waste mass in the Present Landfill is saturated due to groundwater intrusion into the lower portion of the landfill. Though this condition may inhibit gas generation from the completely saturated waste, it will allow for maximum gas generation in adjacent waste. The adjacent waste will more than likely possess moisture contents in the optimal range of 60 to 80 percent. Therefore, a significant portion of the waste in the Present Landfill is likely generating LFG at peak rates.

E.2.4 1994 Methane Survey

The 1994 methane survey provided some excellent data for determining the level of waste decomposition and LFG generation at the site. Off-gassing pressures as high as 0.44 pounds per square inch (psi) (12.2 inches of water) were measured during the survey as well as methane concentrations as high as 50 percent. These kinds of pressures and concentrations are indicative of high levels of waste decomposition and high LFG generation rates. This is expected due to the moist conditions of the waste encountered during the survey. The survey also revealed that concentrations of methane and carbon dioxide were highest in the eastern portion of the landfill, where the waste was youngest and thickest. In addition, the survey revealed that LFG appeared to be contained within the existing groundwater cutoff wall and intercept or drain system (ERM, 1994).

In some areas, shallow subsurface (3 feet) measurements indicated high concentrations of methane (up to 49 percent). These measurements are important because they may indicate the potential for high levels of methane in the proposed ET cover. High levels of methane like those measured in 1994 may not support healthy root growth in the cover, thus reducing the performance of the cover and its ability to transpire water. The survey also provided data on NMOC concentrations. These concentrations appeared to be relatively high, but the instrumentation used and sampling procedure was unclear from available records.

E.2.5 Landfill Gas Generation Rate Estimates

LFG generation estimates are useful in cover design for the following reasons: (1) low permeability covers could force more LFG into the subsurface and to groundwater, (2) low permeability covers may limit oxygen movement into the cover, which could limit root growth and transpiration, and (3) LFG generation rates are needed to evaluate LFG control system requirements and the capacity of control systems, if needed.

Typically, the rate at which wet municipal waste generates gas increases for the first 5 or 6 years after placement in a landfill, and declines thereafter if no additional waste is added. After placement of adequate landfill cover, the waste typically becomes too dry to maintain high gas production rates. Results from field studies show that after 15 years of landfill inactivity, between 60 to 85 of the potential methane production from landfill waste has already been produced (McBean, 1995).

Landfill gas generation rates for the Present Landfill were estimated using EPA's Landfill Gas Emissions Model Version 2.0 (LandGEM). LandGEM uses a first order decay rate equation (equation 1) and estimates annual emissions over any time period specified by the user. Total landfill gas emissions are estimated by using one of the following methods: (1) estimating methane emissions and doubling the result (this assumes a 50 percent methane, 50 percent carbon dioxide LFG mixture), or (2) running the model separately for methane and carbon dioxide and adding the results for total LFG emissions. Methane generation is estimated using two parameters: L_o, the potential methane generation capacity of the refuse, and k, the methane generation rate constant, which accounts for how quickly the methane generation rate decreases once it reaches peak rate. The methane generation is assumed to be at its peak upon closure of the landfill or final placement of waste at the site (Radian International and Eastern Research Group, 1998).

$$Q_{CH_4} = L_o R (e^{-kc} - e^{kt}) \tag{1}$$

where:

Q_{CH4} = Methane generation rate at time t, m^3/yr

L_0 = Methane generation potential, m^3 CH_4/Mg refuse

R = Average annual refuse acceptance rate during active life, Mg/yr

e = Base log, unitless

k = Methane generation rate constant, yr^{-1}

c = Time since landfill closure, yrs (c = 0 for active landfills)

t = Time since the initial refuse placement

LandGEM was used to estimate total landfill gas emissions at the Present Landfill by estimating methane, carbon dioxide, and NMOC emissions individually and then summing the three model results. The following data were input into the model:

- Methane generation rate constant (k) = 0.04/yr
- Methane generation potential (L_0) = 100 m^3/Mg
- Landfill gas mixture is 55 percent methane and 45 percent carbon dioxide
- NMOC concentration = 2,420 ppmv as hexane

The above variables are taken from the Compilation of Air Pollutant Factors (AP-42) (U.S. EPA, 1998). NSPS also has specific variables for estimating LFG generation, but the factors for k and L_o are viewed by the landfill gas industry to generate conservative LFG estimates. In this context, conservative means more rapid degradation with higher peak generation rates. AP-42 states that a lower k value of 0.02 per year may be used sites that receive less than 25 inches of precipitation per year. Though RFETS receives less than 25 inches of precipitation per year, it was decided that the higher k is more suited to the site-specific conditions of the landfill. A k value of 0.02 per year would be more representative of relatively dry waste commonly found in arid and semi-arid climates. As explained in Section 2.3, waste encountered at the site was described as moist and approximately 25 percent of the waste mass is saturated due to groundwater intrusion into the landfill. Therefore, it is more accurate to input the higher k value into the model, because it is indicative of moist waste that typically would be seen in wetter climates. Also, as described in Section 2.4, off-gassing pressures and concentrations measured during the methane survey in 1994 seemed to indicate high levels of gas production, which a higher k value will produce. For comparative purposes, the model was also run for k values of 0.02 per year and 0.05 per year.

The results of the model indicate only relatively low rates of gas generation. The results are depicted graphically in Figures E-1 through E-4. The model predicted a peak LFG generation in 1998, immediately after the closure of the landfill, and LFG generation rates are now declining. The gas generation rates for 1998 with a k value of 0.04 per year were as follows:

- Methane = 31.1 cubic feet per minute (ft^3/min)
- Carbon dioxide = 25.4 ft^3/min
- NMOCs = 0.14 ft^3/min
- Total LFG = 56.7 ft^3/min

These generation rates are low due to the relatively small amount of waste deposited in the landfill. Figure E-1 is a graphical representation of the LandGEM output. It shows the majority (approximately 80 percent) of methane and total LFG production occurring by the year 2025 and almost all potential production by the year 2075. The total LFG generation rate for 1998 for k values of 0.02 per year and 0.05 per year were 35.2 ft^3/min and 64.1 ft^3/min, respectively. These results are similar enough to the results for a k value at 0.04 per year to show that whatever k value is used, the volume of gas generation does not radically change. Therefore, the scope of the LFG evaluation does not change and the effects of LFG on cover performance must be evaluated.

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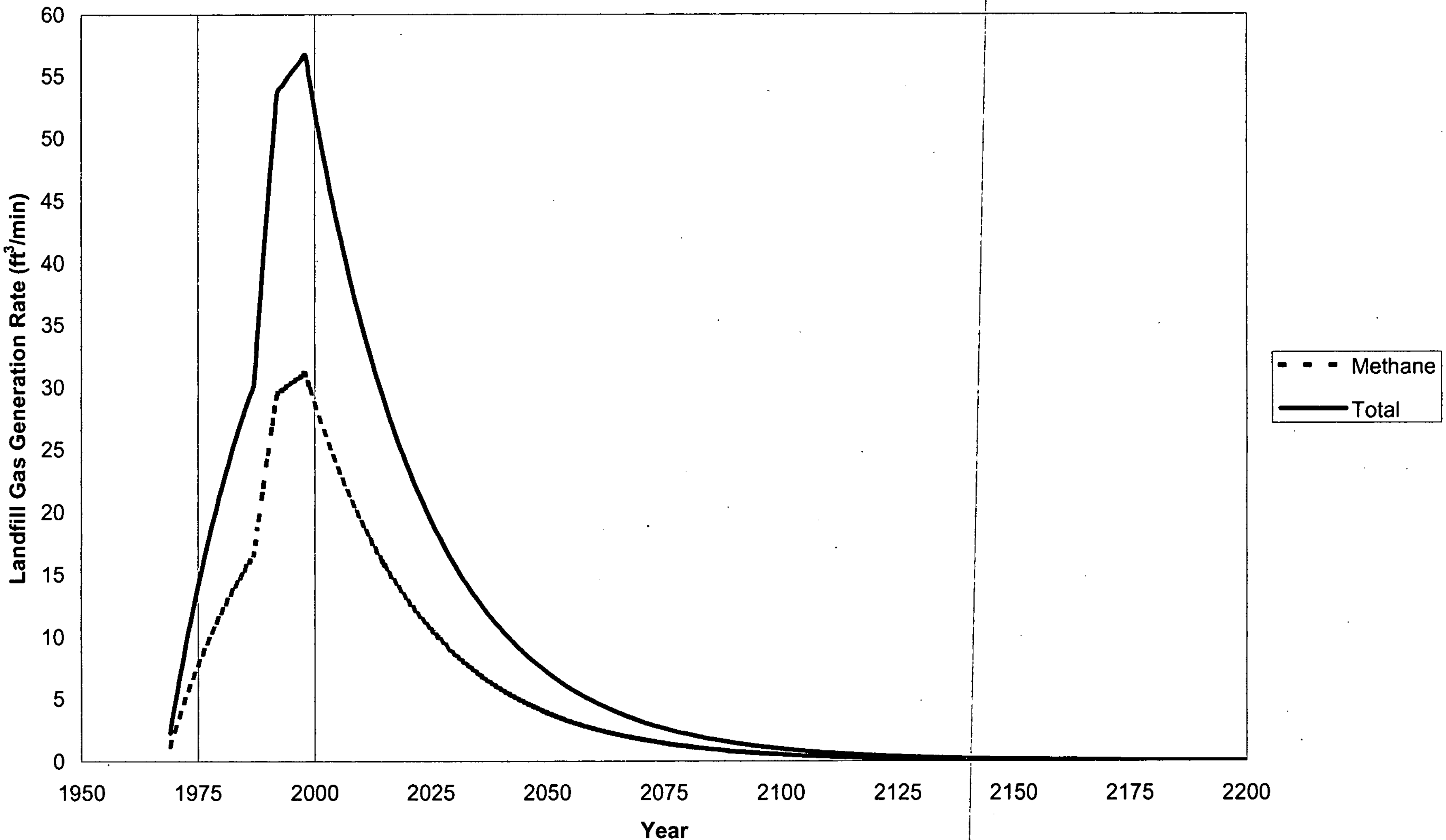

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Landfill Gas Generation at the Present Landfill (k = 0.04)

Figure E-1

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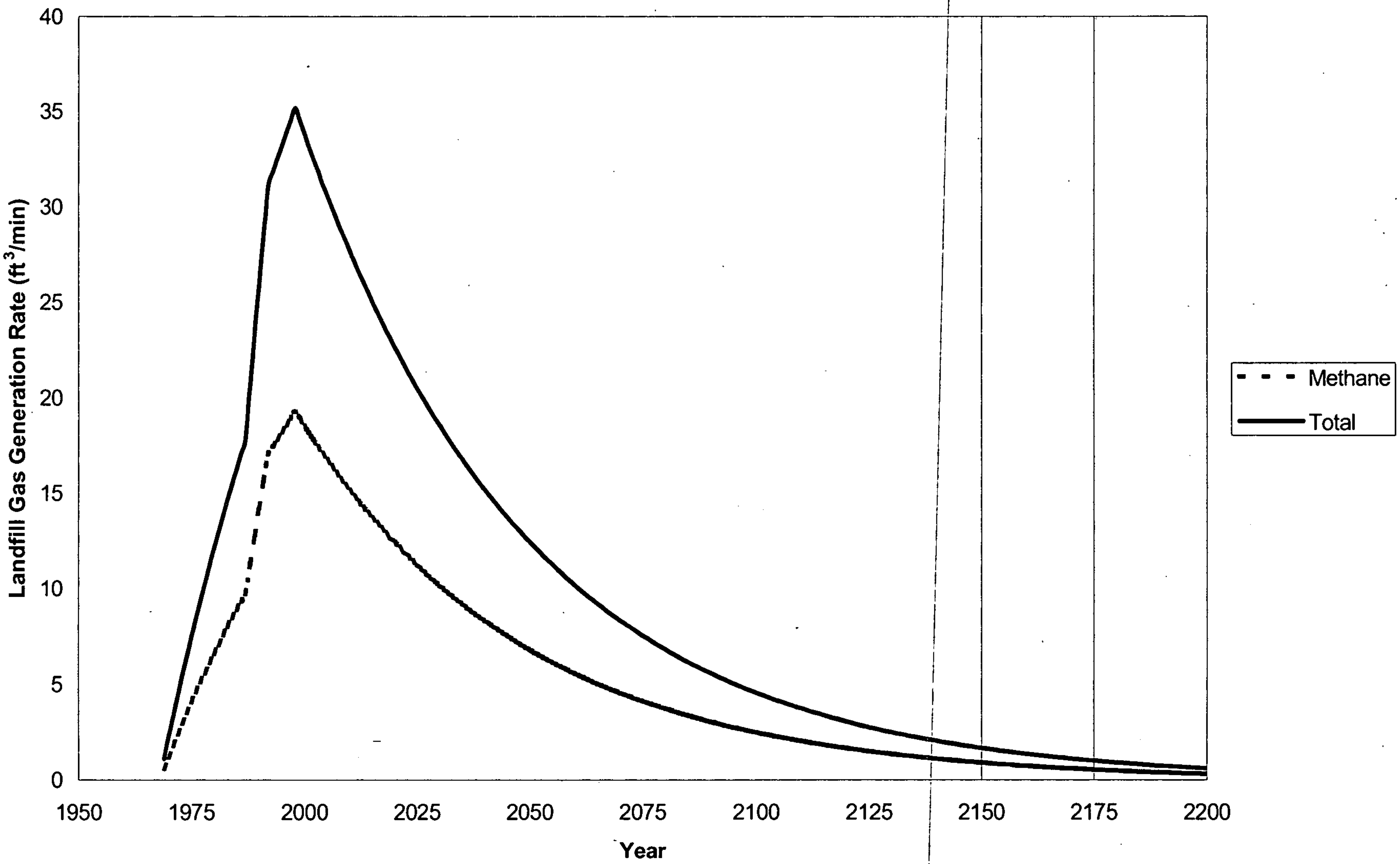

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Landfill Gas Generation at the Present Landfill (k = 0.02)

Figure E-2

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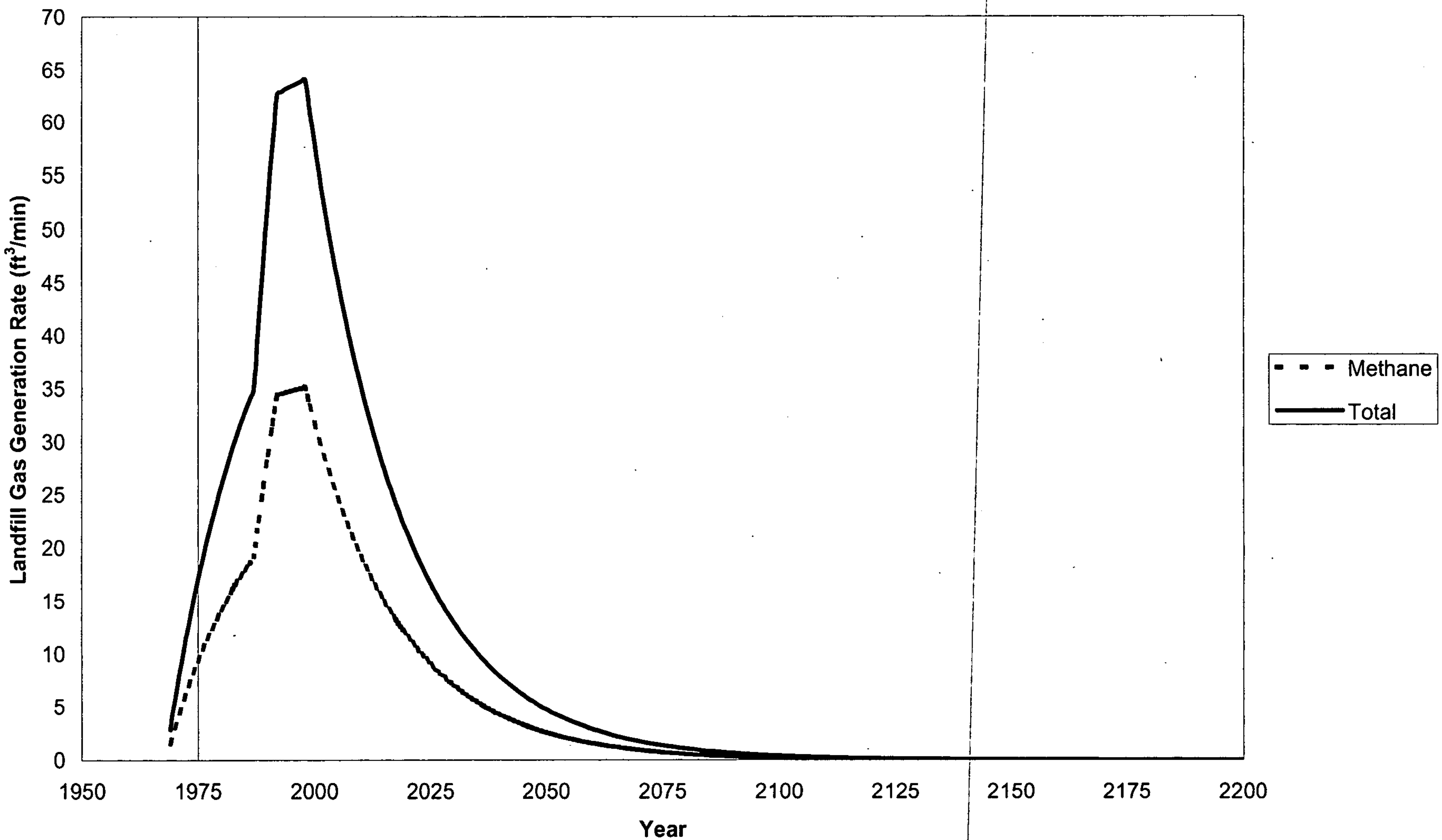

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Landfill Gas Generation at the Present Landfill (k = 0.05)

Figure E-3

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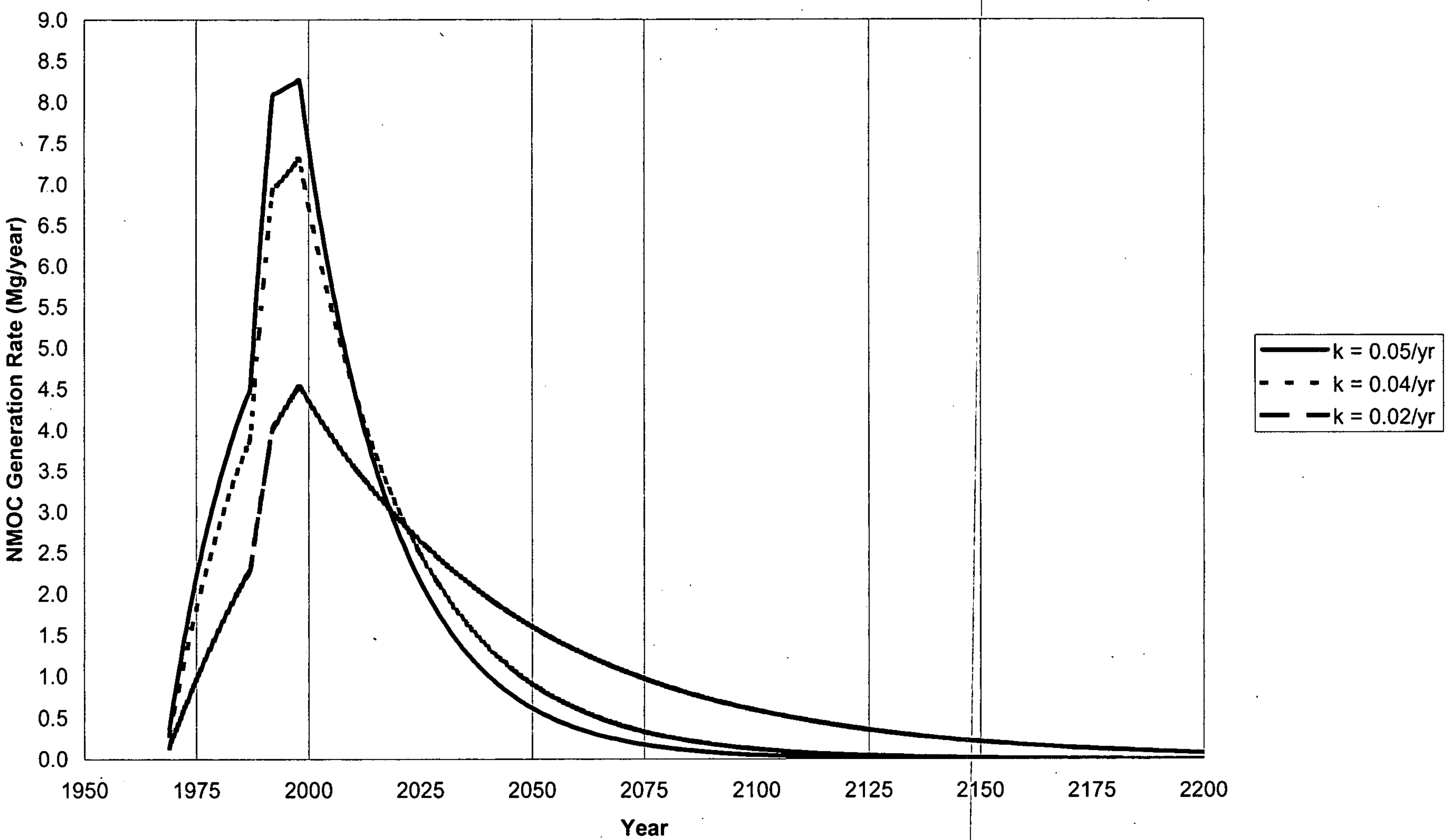

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Estimated NMOC Generation Rates at the Present Landfill

Figure E-4

E.2.6 Gas Phase Transport of Contaminants

Major contaminants of concern at RFETS are HAPs. Specific HAPs measured during the 1994 survey were 1,2-dichloroethene, 1,1,1-trichloroethane, trichloroethene, methylene chloride, acetone, 2-butanone, toluene, xylene (Kaiser-Hill, 1996). The ET cover is not expected to increase HAPs emissions from the landfill or affect any related regulatory requirements that may already apply to the landfill. Since the ET cover is highly permeable, it will not entrap gas within the landfill or cause significant migration in the subsurface.

As described in the next section the cover may reduce gas emissions and gas phase transport at the site by reducing water infiltration into the waste, which leads to drying of the waste, slower decomposition, and reduced LFG production.

E.3 Cover Impacts on Landfill Gas Emissions and Migration

To determine gas emission effects on cover performance, it is necessary to know the flux and velocity of LFG through the cover. In order to estimate the current flux (flowrate/unit area) of LFG from the landfill, the generation rate for 2001 (50.3 ft^3/min) with a k value of 0.04 per year was used. This flowrate was then divided over the entire 21-acre landfill for a LFG flux of 2.80×10^{-5} cubic feet per minute per square foot. This corresponds to an estimated Darcian gas velocity of 2.80×10^{-5} centimeters per second (cm/s) through the cover at 20 percent water content and a gas seepage velocity of 1.4×10^{-4} cm/s. Darcian gas velocities for k values at 0.02 per year and 0.05 per year are 1.78×10^{-5} cm/s and 3.08×10^{-5} cm/s, respectively. Corresponding gas seepage velocities are 8.9×10^{-5} cm/s and 1.54×10^{-4} cm/s, respectively. These values are toward the low end of encountered gas fluxes.

Reducing water infiltration into the cover will greatly reduce the amount of LFG generation and subsequent emissions. As previously described in this report, moisture content is typically the primary controlling factor in LFG generation. Once the ET cover is in place the waste will slowly begin to dry out and generation rates will decline. This will lead to reduced emissions of methane and NMOCs, which will benefit the air quality of the site as well as the cover performance.

In addition to reducing water infiltration, the cover will serve as a medium for the mixing of methane and NMOCs with atmospheric oxygen. This mixing will lead to decomposition of methane and NMOCs into mainly carbon dioxide, heat, and water. The water will then be transpired by plant roots in the cover, preventing any infiltration into the waste below.

E.4 Landfill Gas Impacts on Cover Performance

The main impact LFG may have on cover performance is the inhibition of plant growth on the cover. Well established plant growth and deep root penetration are critical to the success and effectiveness of an ET cover. Therefore, it is important to evaluate the potential effects LFG may have on cover vegetation.

E.4.1 Effect of Methane on Plant Rooting

Methane displaces oxygen, which is required in the soil-rooting medium to maintain healthy root activity. Typically, even low methane levels indicate minimal oxygen concentrations. Currently, there appear to be no reliable data in the scientific literature on what levels of methane are harmful to plants and what minimum subsurface concentrations of oxygen are required to sustain plant growth. In addition, the shallow subsurface of landfills tends to be very dynamic due to "barometric pumping", which is the effect of the diurnal barometric cycle on the landfill. This cycle causes the landfill to "breathe", or inhale and exhale over the course of the average day. This effect can also be exaggerated by pressure fronts moving though the area. Barometric pumping will typically flood the cover with LFG during part of the day and with atmospheric air the other part of the day. This pumping effect may or may not provide enough oxygen to the cover to sustain plant roots during high levels of gas production.

To conservatively evaluate whether or not atmospheric oxygen will be able to enter the cover against the pressure of exiting landfill gas, the exit LFG velocity was estimated. In order to simplify the analysis and be conservative, barometric pumping was not considered as an oxygen driving mechanism into the landfill. The estimated LFG velocity calculated in Section 3.0 converts to 2.42 centimeters per day (cm/day) for a k of 0.04 per year. The LFG velocities for k values of 0.02 per year and 0.05 per year are 1.54 cm/day and 2.66 cm/day, respectively.

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This velocity is greater than would typically be expected for air moving into the cover under normal atmospheric conditions. Therefore, in the absence of barometric pumping LFG may displace all the oxygen in the ET cover as it exits the landfill, and oxygen may not be able to enter the cover to sustain adequate plant transpiration at depth.

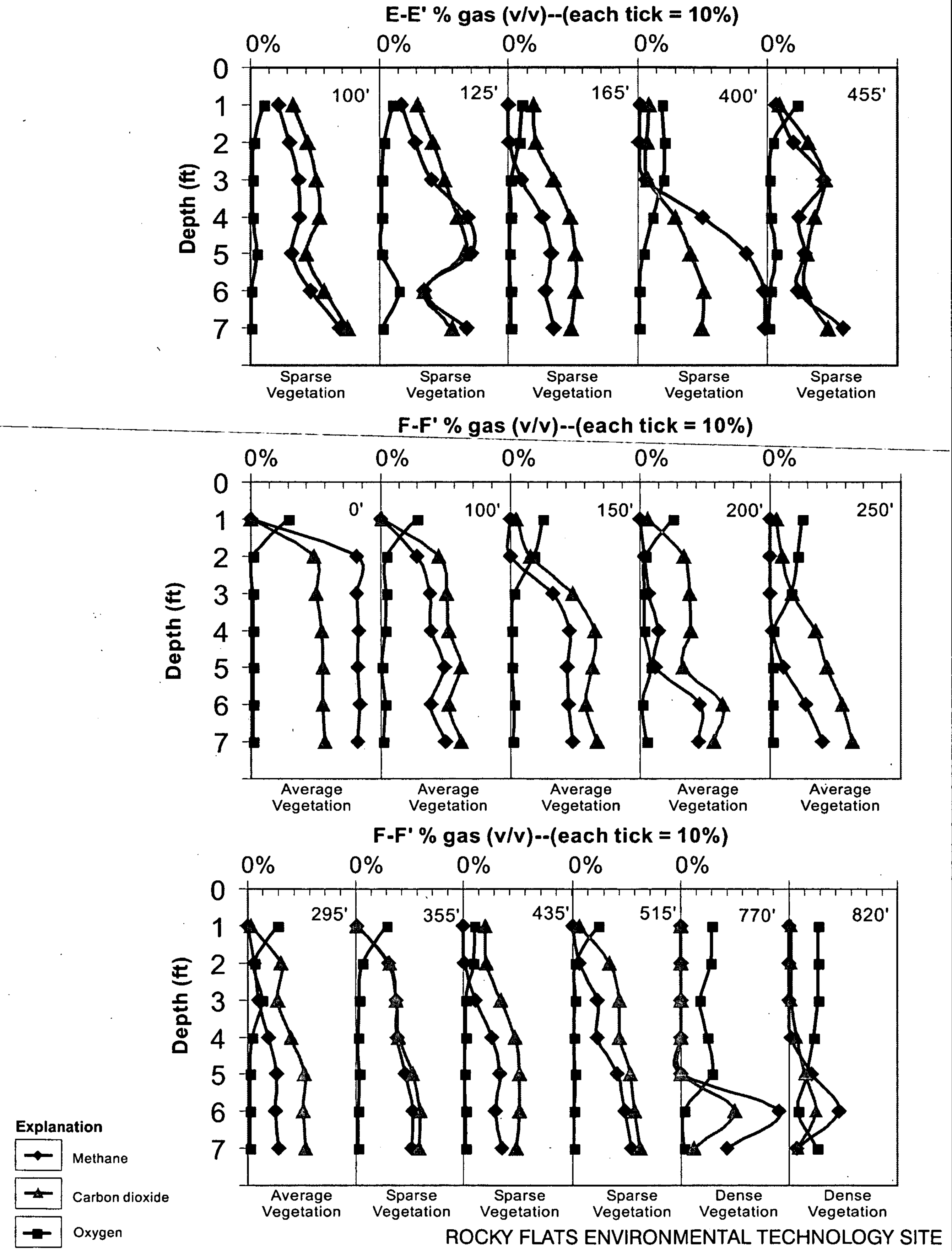
In addition, as described in Section 2.4, the 1994 methane survey revealed high levels of methane in the shallow subsurface. High levels of methane like those measured in 1994 may not support healthy root activity in the cover, thus reducing the performance of the cover and its ability to transpire water. The gas velocity analysis, coupled with shallow subsurface data from 1994, suggest that it may be necessary for the installation of LFG controls to prevent oxygen displacement in the shallow subsurface.

E.4.2 2001 Methane Survey

Recent observations at the Present Landfill show seemingly healthy plant growth on the existing intermediate cover. It is surprising that in light of the data presented above the plants are doing so well. This may be due to greatly reduced levels of methane in the shallow subsurface since the 1994 report. Barometric pumping may also be supplying the current cover with enough oxygen to support plant growth. These observations indicated the need for current data to make a final determination of whether or not LFG controls are required for final closure of the Present Landfill. A new LFG survey was planned to measure methane and oxygen concentrations in the existing cover in order to evaluate the need for LFG venting.

During September 2001, KH conducted a field investigation to examine landfill gas conditions in the existing, interim soil cover over the Present Landfill. The investigation used a soil probe to collect gas samples from the interim cover soils and underlying solid waste. The probe was used to collect samples at 1-foot intervals, up to 7 feet below the cover surface. Probing was conducted on transects across the landfill cover, giving a representative distribution of gas measurement.

Results of the gas probe investigation are depicted graphically in Figure E-5. The results show that oxygen is depleted and methane is elevated at depths of only 1 to 2 feet below the cover



ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Soil Gas Profiles

Figure E-5

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surface. The investigation indicates that gas generation rates in the Present Landfill are causing significantly elevated methane concentrations in the interim cover soils, at levels that will significantly limit plant root growth. The gas probe investigation provides current information to support design decisions on the necessity of the gas-venting layer.

E.5 Landfill Gas Controls

LFG controls will be needed to prevent methane from inhibiting deep root growth and affecting the performance of the ET cover. As discussed in Section 4.0, current data show elevated methane concentrations in the existing interim soil cover. This section presents the conceptual design of a passive venting system to control LFG. Due to the relatively low generation rates anticipated at the Present Landfill, an active landfill gas system is not recommended at this time.

E.5.1 Existing Passive LFG Vents

The existing passive LFG vent wells may be removed during construction of the ET cover. If a landfill gas control system is added as part of the ET cover, there is no need for the existing vents. Information on the design of the existing LFG vent wells, the rationale for their installation, and any monitoring results were unavailable for the current study. Details of the vent well construction will be needed to established appropriate well abandonment methods to remove the vents prior to construction of the final cover over the Present Landfill.

E.5.2 LFG Vent System Design

The conceptual design for a LFG venting system includes a constructed venting layer over the entire Present Landfill waste disposal area, with the ET cover soil-rooting medium placed above the venting layer. An example venting system consists of a gravel or cobble layer (or other approved material with a minimum diameter of ½ inch) with a minimum layer thickness of 6 inches. The granular vent layer should be overlain by an optional geosynthetic fabric layer (12-ounce minimum) to prevent soil intrusion. A geosynthetic fabric may be specified due to the short design life requirement of the vent system. Since significant landfill gas production will

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only occur over the next few decades, it is acceptable if the geosynthetic fabric degrades over time. Installed within the gravel layer will be 2-inch nominal minimum, SDR 17 high-density polyethylene (HDPE) passive landfill gas vent wells extending from the center of the gravel layer to the surface. The vent wells will be connected to a network of horizontal perforated pipes installed within the gravel layer. The vertical vents will be spaced at a minimum density of one vent per acre. Figure E-6 shows conceptual locations of vent wells at the Present Landfill. The top of the vent well may be left open for passive venting, or may use a wind-driven turbine to increase air flow. Passive air flow will oxygenate the venting layer and overlying soil-rooting medium. Figure E-7 is a detail of the vent layer and well.

E.6 Conclusions and Recommendations

The Present Landfill is producing LFG at a high rate due to the high moisture content of waste contained in it, but its overall volume of gas production is relatively low due to the small volume of waste deposited. Measured soil gas profiles within the landfill cover show that LFG controls are needed to ensure vegetative growth is not inhibited and the effectiveness of the ET cover compromised. Unrestricted root growth throughout the full thickness of the cover is important for the proper performance of the ET cover.

The ET cover is not expected to change the regulatory status of the Present Landfill regarding air quality emissions, but a more detailed analysis of air quality requirements for the Present Landfill within the overall RFETS context may be needed. The ET cover will not increase emissions from the landfill compared to current conditions, nor is it expected to change the subsurface migration pattern of LFG at the site. Since the cover is relatively permeable and will be vented, it will not trap LFG within the landfill and cause gas to migrate outward or downward.

Over the long term, LFG generation rates and air emissions will continue to decline, and nearly all of the landfill's gas generation potential is expected to be expended over the next 25 to 75 years.

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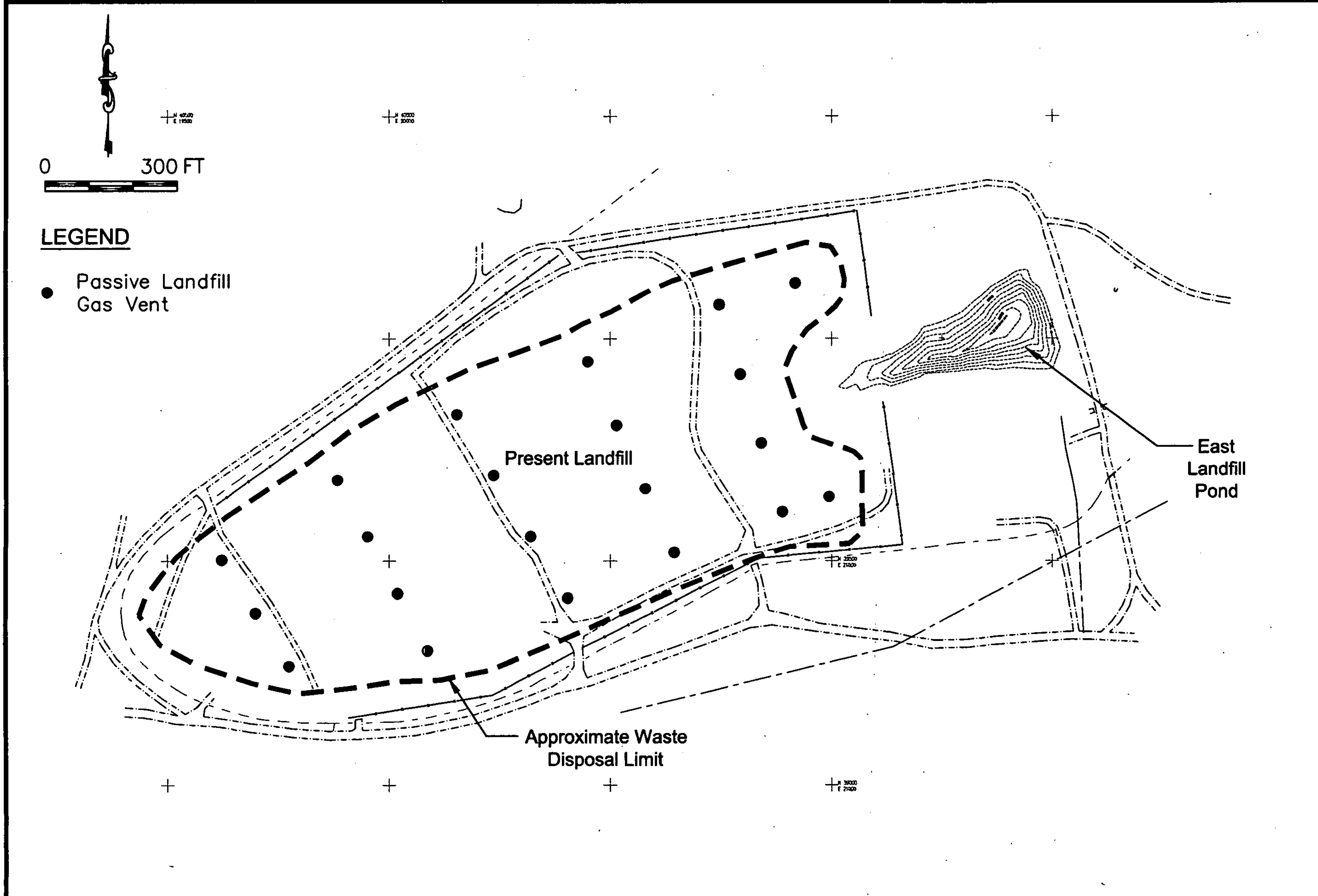
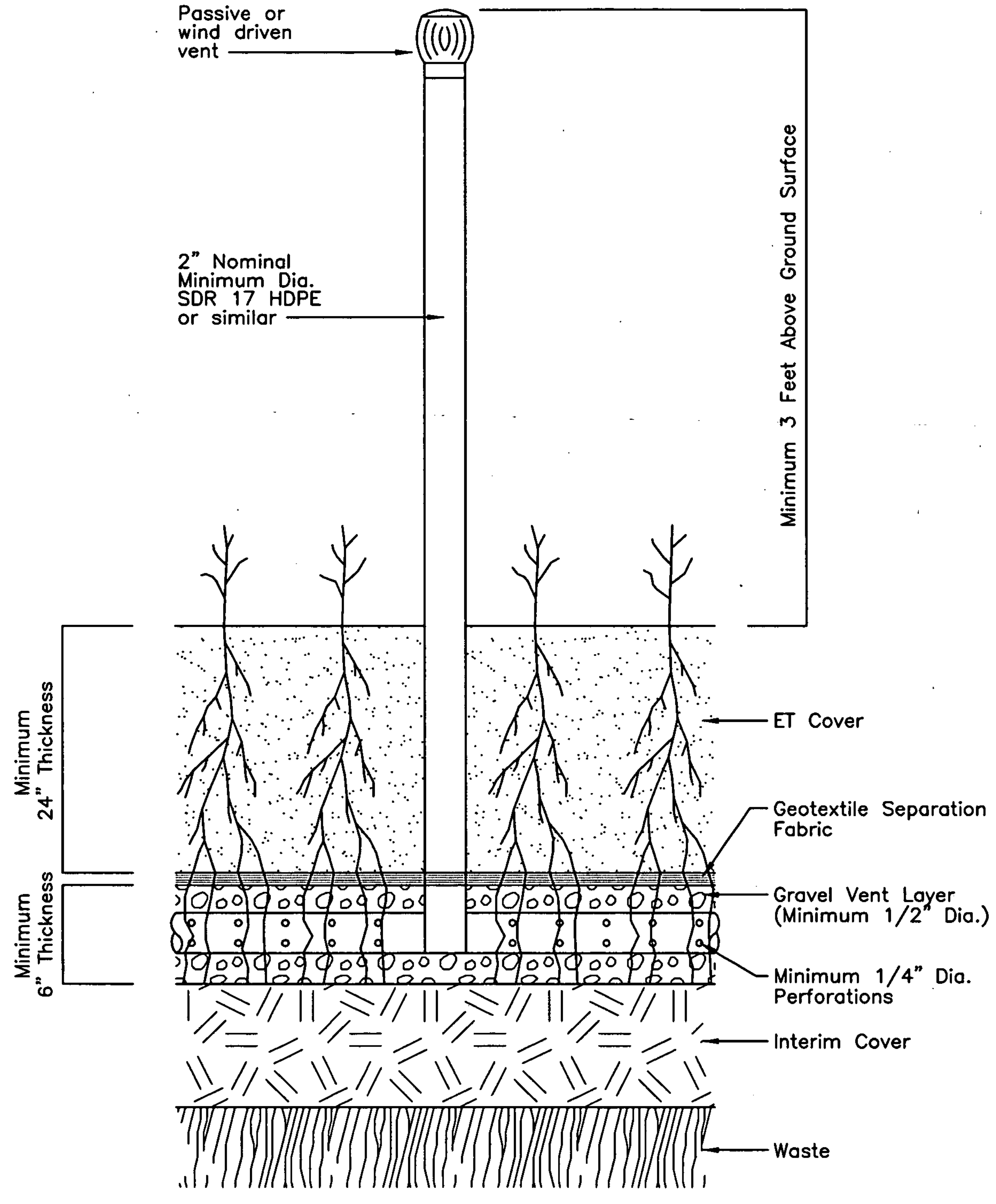
S:\Projects\9373\Drawings\Figures_4-15-02\Landfill\Appendix_E\Figure_E-6_lf.dwg



ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Conceptual Locations of Landfill Gas Wells

Figure E-6



ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

Conceptual Passive Vent Well and Vent Layer Detail

Figure E-7

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Environmental Restoration Management (ERM). 1994. *Rocky Flats Environmental Site Technical Memorandum*. October 1994.

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Appendix F

Erosion Calculations

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RUSLE Summary for Soil Erosion Evaluation

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Table Page

Attachments

Attachment

Appendix F. RUSLE Summary for Soil Erosion Evaluation

The RUSLE (Revised Universal Soil Loss Equation) model was used to calculate slope erosion for the Rocky Flats Environmental Technology Site (RFETS). RUSLE is a widely used model to predict soil loss on any field condition where soil erosion by water is possible (Renard, et al., 1997). The model uses the equation: A = RKLSCP; where A is the predicted average annual soil loss in tons per acre, R is the rainfall-runoff erodibility factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the cover-management factor, and P is the support-practice factor.

F.1 Rainfall-Runoff Erosivity Factor

The rainfall-runoff erosivity factor, R, is an indication of the two most important characteristics of a storm. To determine how erosive a storm is the total amount of rainfall (E) and peak intensity (I) sustained over an extended period of time are calculated (R=E x I). The erosion-index (EI) is a measure of the erosion force of a specific rainfall event. When other factors are constant, storm losses from rainfall are directly proportional to the product of the total kinetic energy of the storm (E) times its maximum 30-minute intensity (I). R is the average annual summation EI value for a normal year's rain.

For the RFETS area, the CITY database was edited (Table F-1) using the Denver city code. The 10 year EI and R factors are set at 50 using the isoerodent map for Colorado (Figure 1, Wischmeier et al., 1978). The EI curve number is set at 82 from the Agriculture Handbook #703, Figure 2.7. Default precipitation and temperature data used are from the Denver CITY code. The frost-free days/year are 134, which is the average calculated for the Flatirons Series from the Soil Survey of Golden Area, Colorado (Price, 1980, p.202).

F.2 Soil Erodibility Factor

The soil-erodibility factor, K, represents both susceptibility of soil to erosion and the rate of runoff, as measured for the standard unit plot condition. The standard unit plot condition is an erosion plot 72.6 ft long on a 9 percent slope, maintained in continuous fallow and tilled up and

Table F-1. Edit City Database for Rocky Flats

```
+------------------< Create/Edit City Database Set 1.06 >--------------------
+
|
|
|  city code: 6004      city: ROCKY FLATS       state: CO
|  total P: 15.3"       EI curve #: 82             Freeze-Free days/year: 134
|
|elevation(ft): 6000   10 yr EI: 50                              R factor: 50
|
|--- Mean P(") ---------- Tav (deg. F) --------------- %EI --------- %EI ------
|
|      1: 0.51             1: 28.45                      1: 0           13: 29.8
|
|      2: 0.69             2: 31.45                      2: 0           14: 44.5
|
|      3: 1.21             3: 36.35                      3: 0.1         15: 64.2
|
|      4: 1.81             4: 46.4                       4: 0.1         16: 83.1
|
|      5: 2.47             5: 56.15                      5: 0.2         17: 92.2
|
|      6: 1.58             6: 66.5                       6: 0.2         18: 96.4
|
|      7: 1.93             7: 72.9                       7: 0.5         19: 98.1
|
|      8: 1.53             8: 71.5                       8: 1.2         20: 99.3
|
|      9: 1.23             9: 63                         9: 3.1         21: 99.7
|
|     10: 0.98            10: 51.4                      10: 6.7         22: 99.8
|
|     11: 0.82            11: 37.65                     11: 14.4        23: 99.8
|
|     12: 0.55            12: 31.6                      12: 20.1        24: 99.9
|
|
|
|
|
+------------------< F7 Saves, Esc Returns to CITY Main Menu >----------------
+
```

down hill periodically to control weeds and break crusts that form on the surface of the soil. The soil structure, organic content, and soil management affect the K factor of a soil. Soils high in clay are resistant to detachment and consequently have low K values. Even though coarse textured soils, such as sandy soils, are easily detached, they have low runoff and therefore have low K values. Medium textured soils, such as silt and loam, have moderate K values because they are moderately susceptible to detachment and produce moderate runoff. The soils that are most subject to erosion (high K values) are those with a high silt content, as they are easily detached, tend to crust, and produce high rates of runoff. The addition of organic matter decreases erosion of soil, and the K factor, by reducing detachment and increasing infiltration. Extrapolation of the K factor nomograph (Figure 3-1, Agriculture Handbook No. 703) beyond an organic matter of 4% is not permitted in the RUSLE model. Although a K factor can be selected to represent a soil in its natural condition, past management can increase a soil's erodibility. The K factor may need to be increased if the subsoil is exposed, the organic matter has been depleted, the soil's structure has been destroyed or soil compaction has reduced permeability.

The K factor from the nomograph was calculated at 0.248. The value is an estimate based on percentages of silt and very fine sand, and clay from particle size distribution testing results. This seasonally variable K factor is also based on soil structure, soil permeability, and a coarse fragment correction. These parameters are selected based on particle size analysis, gravel correction and hydraulic conductivity. The saturated hydraulic conductivity calculated from testing is 0.72 in/hr. Therefore, the permeability code is 3 and the hydrologic soil group is B from Table 3-3 (Agriculture Handbook No. 703). Hydrologic soil group B consists of soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission. The percent rock cover and the hydrologic soil group are applied to the estimated K factor and an average annual K factor is calculated. This factor is 0.27 and is used as an input to the model (Table F-2).

F.3 Slope Length and Steepness Factor

The slope length factor, L, is the ratio of soil loss from the area of interest to that from a 72.6-foot length slope of the same soil type and gradient. The slope length is defined as the flow path

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Table F-2. RUSLE version 1.06								
	A =	(R)	(K)	(LS)	(C)	(P)		
Pt. Carson								
A1 4% Slope	4.89,2.22,1.11,0.47,0.14,0.03	50	0.37	0.80	GC varied by 0-100%	1.00		
A2 4% Slope	28.47, 12.65, 6.33,2.68,0.82,0.18	50	0.37	3.42	GC varied by 0-100%	1.00		
A3 4:1 Slope	27.47, 12.21, 6.11,2.58,0.79,0.18	50	0.37	3.30	GC varied by 0-100%	1.00		
A, Weighted Avg	14.57, 6.48,3.24,1.36,0.42,0.08							
Assume: unit wt of soil = 1.20 g/cc = 75 pcf			1. Amount of soil in one acre, one ft. deep					
60% ground cover since mulch			(75 pcf)(1 ft)(43560 ft²/ac)(ton/2000 lb.) = 1,634 tons/acre					
will be used on flatter Slopes and								
erosion mat on steeper Slope.			2. Length of time					
60% is considered to be a conservative			1,634 tons/ac =		1,201 yrs.			
estimate for long term vegetative growth.			1.36 tons/ac/yr					
Erosion loss 1.36 tons/ac/yr								
Rocky Flats								
Present Landfill Proposed Grading Plan 320' Slope	1.90	50	0.27	4.31	0.032	1.00		
Present Landfill Proposed Grading Plan 420' Slope	1.20	50	0.27	2.86	0.032	1.00		
Present Landfill Proposed Grading Plan 600' Slope	0.68	50	0.27	1.58	0.032	1.00		
Present Landfill Existing East Slope	2.80	50	0.27	6.17	0.034	1.00		
SEPs	1.70	50	0.27	3.86	0.033	1.00		
Assume: density of soil = 1.80g/cc = 112.37 pcf			1. Amount of soil in one acre, one ft. deep.					
			(112.37 pcf)(1 ft)(43560 ft2/ac)(ton/2000 lb.) = 2,447 tons/acre					
			2. Amount of soil in one acre, one-half ft. deep.					
			(112.37 pcf)(1/2 ft)(43560 ft2/ac)(ton/2000 lb.) = 1,224 tons/acre					
Erosion loss for Present Landfill Proposed Grading Plan								
1.90 tons/ac/yr			1a. Length of time			2a. Length of time		
			2,447 tons/ac =		1,288 yrs	1,224 tons/ac =		644 yrs
			1.90 tons/ac/yr			1.90 tons/ac/yr		
Erosion loss for Present Landfill Proposed Grading Plan								
1.20 tons/ac/yr			1b. Length of time			2b. Length of time		
			2,447 tons/ac =		2,039 yrs	1,224 tons/ac =		1,020 yrs
			1.20 tons/ac/yr			1.20 tons/ac/yr		
Erosion loss for Present Landfill Proposed Grading Plan								
0.68 tons/ac/yr			1c. Length of time			2c. Length of time		
			2,447 tons/ac =		3,599 yrs	1,224 tons/ac =		1,800 yrs
			0.68 tons/ac/yr			0.68 tons/ac/yr		
Erosion loss for Present Landfill Existing Slope D			1d. Length of time			2d. Length of time		
2.80 tons/ac/yr			2,447 tons/ac =		874 yrs	1,224 tons/ac =		437 yrs
			2.80 tons/ac/yr			2.80 tons/ac/yr		
Erosion loss for SEPs			1e. Length of time			2e. Length of time		
1.70 tons/ac/yr			2,447 tons/ac =		1,439 yrs	1,224 tons/ac =		720 yrs
			1.70 tons/ac/yr			1.70 tons/ac/yr		

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Table F-2. RUSLE version 1.06

	A =	(R)	(K)	(LS)	(C)	(P)		
Ft. Carson								
A1 4% Slope	4.99,2.22,1.11,0.47,0.14,0.03	50	0.37	0.60	GC varied by 0-100%	1.00		
A2 4% Slope	28.47, 12.65, 6.33,2.66,0.82,0.19	50	0.37	3.42	GC varied by 0-100%	1.00		
A3 4:1 Slope	27.47, 12.21, 6.11,2.56,0.79,0.18	50	0.37	3.30	GC varied by 0-100%	1.00		
A, Weighted Avg.	14.57, 6.48,3.24,1.36,0.42,0.09							
Assume: unit wt of soil = 1.20 g/cc = 75 pcf			1. Amount of soil in one acre, one ft. deep.					
60% ground cover since mulch			(75 pcf)(1 ft)(43560 ft²/ac)(ton/2000 lb.) = 1,634 tons/acre					
will be used on flatter Slopes and								
erosion mat on steeper Slope.			2. Length of time					
60% is considered to be a conservative			1,634 tons/ac =		1,201 yrs.			
estimate for long term vegetative growth.			1.36 tons/ac/yr					
Erosion loss 1.36 tons/ac/yr								
Rocky Flats								
Present Landfill Proposed Grading Plan 320' Slope	1.90	50	0.27	4.31	0.032	1.00		
Present Landfill Proposed Grading Plan 420' Slope	1.20	50	0.27	2.66	0.032	1.00		
Present Landfill Proposed Grading Plan 600' Slope	0.68	50	0.27	1.56	0.032	1.00		
Present Landfill Existing East Slope	2.80	50	0.27	6.17	0.034	1.00		
SEPs	1.70	50	0.27	3.86	0.033	1.00		
Assume: density of soil = 1.80g/cc = 112.37 pcf			1. Amount of soil in one acre, one ft. deep.					
			(112.37 pcf)(1 ft)(43560 ft2/ac)(ton/2000 lb.) = 2,447 tons/acre					
			2. Amount of soil in one acre, one-half ft. deep.					
			(112.37 pcf)(1/2 ft)(43560 ft2/ac)(ton/2000 lb.) = 1,224 tons/acre					
Erosion loss for Present Landfill Proposed Grading Plan								
1.90 tons/ac/yr			1a. Length of time			2a. Length of time		
			2,447 tons/ac =		1,288 yrs	1,224 tons/ac =		644 yrs
			1.90 tons/ac/yr			1.90 tons/ac/yr		
Erosion loss for Present Landfill Proposed Grading Plan								
1.20 tons/ac/yr			1b. Length of time			2b. Length of time		
			2,447 tons/ac =		2,039 yrs	1,224 tons/ac =		1,020 yrs
			1.20 tons/ac/yr			1.20 tons/ac/yr		
Erosion loss for Present Landfill Proposed Grading Plan								
0.68 tons/ac/yr			1c. Length of time			2c. Length of time		
			2,447 tons/ac =		3,599 yrs	1,224 tons/ac =		1,800 yrs
			0.68 tons/ac/yr			0.68 tons/ac/yr		
Erosion loss for Present Landfill Existing Slope D			1d. Length of time			2d. Length of time		
2.80 tons/ac/yr			2,447 tons/ac =		874 yrs	1,224 tons/ac =		437 yrs
			2.80 tons/ac/yr			2.80 tons/ac/yr		
Erosion loss for SEPs			1e. Length of time			2e. Length of time		
1.70 tons/ac/yr			2,447 tons/ac =		1,439 yrs	1,224 tons/ac =		720 yrs
			1.70 tons/ac/yr			1.70 tons/ac/yr		

between the source of overland flow to the location of concentrated flow or sediment deposition. Channels that collect the flow from numerous rills are generally considered to be slope-ending concentrated flow channels. Slope lengths longer than 1000 ft should not be used because the reliability of RUSLE using long slope lengths is questionable, because generally, flow becomes concentrated on most landscapes before such long slope lengths.

The slope length and gradient were measured for several of the key transects on the Present Landfill. The values for the LS factor varied depending on these measurements (Table F-2).

F.4 Cover-Management Factor

The cover-management factor, C, indicates how a conservation plan will affect the average annual soil loss and how that soil-loss potential will be distributed in time during construction activities and final implementation of management proposals. RUSLE uses a subfactor method to compute soil loss ratios (SLR), which are the ratios at any given time in a cover management sequence to soil loss from the unit plot, an area under clean-tilled continuous-fallow conditions. Soil loss ratios vary with time as canopy, ground cover, roughness, soil biomass and consolidation change. These factors are used to compute a soil loss ratio value along with considerations of prior land use and antecedent soil moisture. Ground surface cover is material in contact with the soil surface that intercepts raindrops and slows surface runoff. Surface cover includes all cover that is present, such as rock fragments, live vegetation, cryptogams, or plant residue that are large enough or attached securely enough that they will not be removed by runoff. RUSLE uses the percent of the surface covered to compute how surface cover affects erosion. Surface roughness allows water to pond in depressions and reduces the erodibility of rainfall and water flow.

The factors necessary to compute a value for C begin with selecting a plant community. The plant community chosen for RFETS is a short-grass prairie because it is more conservative than desert grassland for total annual site potential biomass production. The value selected is 600 pounds per acre for the average annual production of air-dry vegetation (Price, 1980 p. 42). The canopy cover has an estimated value of 20.8, while the surface litter is estimated at 18 (Kulakow, 2001). It is assumed that after being established the RFETS plant community will have a relatively constant amount of canopy cover, surface and subsurface residues and root mass. The percent of surface covered by rock fragments is calculated from the gravel correction based on particle size analysis. The resulting calculated C factor value of approximately 0.033 is consistent with published values for undisturbed rangeland.

F.5 Support Practice Factor

The support practice factor, P is the ratio of soil loss from the applied management practice to that with straight row farming up-and-down slope. Topographic features that influence the direction, concentration, and velocity of runoff are created by support practices. These features reflect the impact of support practices on the average annual erosion rate.

When there are no erosion control practices, such as contouring and terracing, RUSLE computes a value of 1.00. Because there will be no contouring or terracing on the cover designs at either site an input value of 1.00 is used for all simulations.

F.6 Results

Slope erosion for RFETS is calculated using the RUSLE model. The input parameters used for this exercise are given in Table F-2. Attachment F1 presents the 'input screens' for the RUSLE model simulations. The attachment shows the parameters used and corresponding results for the proposed Present Landfill simulation.

The results for the RUSLE modeling exercise are shown in Table F-2. Using conservative input parameters the time for one foot of soil to erode from the landfill varies from approximately 874 years to 1439 years. The existing east slope on the present landfill shows that 6 inches of soil will erode in 437 years, this is consistent with field observations, which show considerable gullying.

References

Kulakow, P. 2001. RCRA-Equivalent Cover Demonstration Project: Time 0 Sampling and Analysis, Results for Assessment of Plant Root Development in Alternative Cover Plots at Rocky Mountain Arsenal. Department of Agronomy, Kansas State University, Manhattan, KS. 14pp.

Price, A.B., and Amen, A.E. 1980. *Soil Survey of Golden Area, Colorado- Parts of Denver, Douglas*, Jefferson, and Park Counties. U.S. Department of Agriculture, Soil Conservation Service, In cooperation with Jefferson County and the Colorado Agricultural Experiment Station. 405 pp.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder, coordinators. 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture, Agriculture Handbook No. 703, 404 pp.

Wischmeier, W.H., and Smith, D.D. 1978. Predicting rainfall erosion losses-a guide to conservation planning. U.S. Department of Agriculture, Agriculture Handbook No. 537, 58 pp.

Attachment F1

RUSLE DOS Input Screens

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Rocky Flats Environmental Technology Sites
Present Landfill Proposed Grading Plan
RUSLE Dos input screens:

```
       File         Exit         Help         Screen
+---------------------------< Rainfall Factor 1.06 >----------------------------+
|                                                                               |
|                          city code: 6004    ROCKY FLATS          CO            |
|                    Initial R value: 50                                         |
|                   slope gradient %: 20                                         |
|               adjust for ponding?: 2                                           |
|                                                                               |
|                          +-------------------------+                          |
|                          | R factor = 50           |                          |
|                          |                         |                          |
|                          | (press Esc to dismiss)  |                          |
|                          +-------------------------+                          |
|                                                                               |
+----------------------------------< Esc exits >--------------------------------+
Tab  Esc F1   F9
FUNC esc help info
```

```
      File        Exit        Help        Screen
+------------------< Seasonally Variable K Factor 1.06 >----------------------+
¦   % of silt and very fine sand  (e.g. 66): 32                               ¦
¦                           % clay  (e.g. 17): 12                             ¦
¦           % of organic matter  (e.g. 2.8): 0                                ¦
¦                      soil structure code #: 3                               ¦
¦                  soil permeability class #: 3                               ¦
¦               coarse fragment correction #: 2                               ¦
¦                                                                             ¦
¦                                                                             ¦
¦            -> adjustment for coarse fragments <-                            ¦
¦                  percent by wt. > 3 in. (75mm): 0                           ¦
¦ % by wt. of < 3" which passes #10 sieve (<2mm): 83                          ¦
¦                      +--------------------------------+                     ¦
¦                      ¦ K Factor from nomograph: 0.248 ¦                     ¦
¦                      ¦                                ¦                     ¦
¦                      ¦ (press Esc to dismiss)         ¦                     ¦
¦                      +--------------------------------+                     ¦
¦                                                                             ¦
¦                                                                             ¦
¦                                                                             ¦
+----------------------------------< Esc exits >------------------------------+
Tab  Esc F1  F9
FUNC esc help info
```


252

```
      File         Exit         Help         Screen
+------------------< Seasonally Variable K Factor 1.06 >--------------------+
¦     city code: 6004_   ROCKY FLATS         CO       estimated K: 0.248     ¦
¦ % rock cover: 17    # yrs to consolidate: 17   hyd. group: 2              ¦
¦ soil series: Flatirons          surface texture: sandy loam               ¦
¦                                                                            ¦
¦  1/1-1/15         0.0      0.246    ¦  7/1-7/15          14.7       0.265  ¦
¦  1/16-1/31        0.1      0.282    ¦  7/16-7/31         19.7       0.211  ¦
¦  2/1-2/15         0.0      0.325    ¦  8/1-8/15          18.9       0.166  ¦
¦  2/16-2/28        0.1      0.372    ¦  8/16-8/31          9.1       0.133  ¦
¦  3/1-3/15         0.0      0.419    ¦  9/1-9/15           4.2       0.104  ¦
¦  3/16-3/31        0.3      0.479    ¦  9/16-9/30          1.7       0.094  ¦
¦  4/1-4/15         0.7      0.553    ¦  10/1-10/15         1.2       0.108  ¦
¦  4/16-4/30        1.9      0.633    ¦  10/16-10/31        0.4       0.123  ¦
¦  5/1-5/15         3.6      0.66     ¦  11/1-11/15         0.1       0.142  ¦
¦  5/16-5/31        7.7      0.527    ¦  11/16-11/30        0.0       0.163  ¦
¦  6/1-6/15         5.7      0.415    ¦  12/1-12/15         0.1       0.186  ¦
¦  6/16-6/30        9.7      0.331    ¦  12/16-12/31        0.1       0.213  ¦
¦                                                                     -----  ¦
¦   EI DIST.: 82        FREEZE-FREE DAYS: 134   AVERAGE ANNUAL K:     0.27   ¦
¦    R VALUE: 50     Kmin = 0.09 on 9/18     Kmax = 0.67 on 5/7              ¦
+--------------------------------< Esc exits >------------------------------+
Tab  Esc F1   F2  F3   F4   F6   F9
FUNC esc help clr cont call list info
```

```
     File       Exit        Help        Screen
+-----------------------------< LS Factor 1.06 >-------------------------------+
|                                                                              |
|  number of segments: 1          segment lengths are measured: 2              |
|                                                                              |
|        soil texture: sandy loam                                              |
|    general land use: 6                                                       |
|------------------------------------------------------------------------------|
|                          1                                                   |
| Gradient (%) of Segment   20                                                 |
| Length of Segment (ft)    320                                                |
| Segment LS               4.308                                               |
|-----+------------------------------------------------------------+-----------|
|     | overall LS = 4.31; equiv. slope = 20 %; horiz. length = 320 ft|         |
|     +------------------------------------------------------------+           |
|                                                                              |
|                                                                              |
|                                                                              |
|                                                                              |
|                                                                              |
|                                                                              |
+---------------------------------< Esc exits >--------------------------------+
Tab  Esc F1   F3   F9
FUNC esc help cont info
```

```
      File         Exit         Help        Screen
+-------------------------< Time-invariant C 1.06 >----------------------------+
¦       where get vegetation information?: 1                                   ¦
¦                                                                              ¦
¦                    plant community code: 4                                   ¦
¦annual site production potential (lb/ac): 600                                 ¦
¦   effective root mass (lb/ac) in top 4": 600                                 ¦
¦                          % canopy cover: 21                                  ¦
¦                average fall height (ft): 0.5        +-----------+            ¦
¦  roughness (in) for the field condition: 0.8        ¦ C = 0.032 ¦            ¦
¦   has there been mechanical disturbance: 1          +-----------+            ¦
¦                                                                              ¦
¦                                                                              ¦
¦ total % ground cover (rock and residue): 31.94                               ¦
¦     % surface covered by rock fragments: 17                                  ¦
¦      % vegetative residue surface cover: 18                                  ¦
¦  surface cover function; B-value choice: 1          landuse shown in LS: 6   ¦
¦                                                                              ¦
¦                                                                              ¦
¦                                                                              ¦
¦ enter avg. annual values!                                                    ¦
+------------------------------< Esc to continue >-----------------------------+
Tab  Esc F1   F3   F9
FUNC esc help cont info
```


255

```
       File        Exit        Help        Screen
+-----< P Factor - Infrequent Disturbance, Mechanical Disturbance 1.06 >-------+
¦                          city code: 6004    ROCKY FLATS         CO           ¦
¦               equivalent slope (%): 20                                       ¦
¦              soil hydrologic class: 2                                        ¦
¦                                 site description                             ¦
¦ % cover: 1) at time of disturbance: 10     2) at consolidation: 32           ¦
¦  roughness (in): 1) at disturbance: 0.8    2) at consolidation: 0.8          ¦
¦                                 timing description                           ¦
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Soil Loss and Sediment Yield Computation Worksheet

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Appendix G

Soils Descriptions

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Appendix G. Soil Descriptions

The following descriptions are taken from the United States Department of Agriculture Soil Conservation Service publication entitled Soil Survey of Golden Area, Colorado.

G.1 Flatirons Series

The Flatirons series consists of deep, well drained soils on high terraces, hill slopes, and piedmonts. The soils formed in most commonly noncalcareous, cobbly, stony, gravelly, and loamy material of the Rocky Flats Alluvium. The slope is 0 to 3 percent. The average annual precipitation is 15 to 17 inches. The average annual temperature is 47°F. The average frost-free season ranges from about 126 to 142 days. Elevation ranges from 6,000 to 6,800 feet.

These soils are clayey-skeletal, montmorillonitic, mesic Aridic Paleustolls.

Typical pedon of Flatirons very cobbly sandy loam, 0 to 3 percent slopes (fig. 9), 60 feet west and 750 feet south of the northeast corner of sec. 20, T. 2 S., R. 70 W.

A11-0 to 6 inches; very dark grayish brown (1 OYR 3/2) very cobbly sandy loam, very dark brown (1 OYR 2/2) moist; moderate medium granular structure; soft, very friable, slightly sticky; 20 percent cobbles, 40 percent gravel; neutral; clear smooth boundary.

A12-6 to 13 inches; very dark grayish brown (10YR 3/2) very cobbly sandy loam, very dark grayish brown (10YR 3/2) moist; weak medium subangular, blocky structure parting to moderate medium granular; soft, very friable, slightly sticky; 20 per cobbles, 40 percent gravel; slightly acid; abrupt wavy boundary.

B21t-13 to 21 inches; reddish brown (5YR 5/4) very gravelly clay, reddish brown (5YR 4/4) moist; strong medium prismatic structure parting to strong medium angular blocky; extremely hard, very firm, very sticky; 15 percent cobbles, 45 percent gravel; many thick clay films on faces of peds; medium acid; gradual smooth boundary.

B22t-21 to 38 inches; strong brown (7.5YR 5/6) very gravelly sandy clay, strong brown (7.5YR 4/6) moist, strong medium prismatic structure parting to strong medium angular blocky; very hard, firm, very sticky; 15 percent cobbles, 45 percent gravel; common moderately thick clay films on faces of peds; slightly acid; gradual smooth boundary.

B23t-38 to 47 inches; strong brown (7.5YR 5/8) very gravelly sandy clay, strong brown (7.5YR 5/6) moist, strong medium prismatic structure parting to strong medium angular blocky; hard, friable, very sticky; 15 percent cobbles, 40 percent gravel; common moderately thick clay films on faces of peds; neutral; gradual wavy boundary.

B3-47 to 60 inches; strong brown (7.5YR 5/8) very gravelly sandy clay loam, strong brown (7.5YR 5/6) moist; weak coarse prismatic structure parting to weak coarse subangular blocky; hard, friable, very sticky; 15 percent cobbles, 40 percent gravel; neutral.

The mollic epipedon is 10 to 20 inches thick. The solum is 40 to 60 inches or more thick. The content of rock fragments ranges from 35 to 80 percent.

The A horizon has hue of 10YR or 7.5YR, value of 3 to 5 dry and 2 or 3 moist, and chroma of 2 or 3. It is very cobbly sandy loam or very stony sandy loam. Reaction is slightly acid to mildly alkaline.

The upper part of the B2t horizon has hue of 5YR or is redder; it has value of 5 or 6 dry and 4 or 5 moist and chroma of 4 to 6. The lower part of the B2t horizon may also have hue of 7.5YR or 10YR; it has value of 5 or 6 dry and 4 or 5 moist and chroma of 5 to 8. The B2t horizon is very gravelly clay, very gravelly sandy, very gravelly clay loam, or very cobbly sandy clay. Reaction is neutral to medium acid.

In some places there is a C horizon at a depth of less than 60 inches. It has hue of 10YR through 2.5YR.

45-Flatirons very cobbly sandy loam, 0 to 3 percent slopes. This is a deep, well drained soil on high terraces and piedmonts. It formed in noncalcareous, stony to gravelly, and loamy material of the Rocky Flats Alluvium. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47° F, and the average frost-free season is 126 to 142 days. Elevation is 6,000 to 6,600 feet.

Typically, the surface layer is neutral and slightly acid, very dark grayish brown very cobbly sandy loam about 13 inches thick. The subsoil in the upper 8 inches is medium acid, reddish brown very gravelly clay; in the next 26 inches it is slightly acid and neutral, strong brown very gravelly sandy clay; and below that to a depth of 60 inches it is neutral, strong brown very gravelly sandy clay loam.

Included in mapping are small areas of calcareous soils near the edge of terraces, Veldkamp soils in positions similar to those of the Flatirons soil, soils near the mouth of Coal Creek Canyon that have a very stony surface layer, and soils that have a dark surface layer more than 20 inches thick and are on mounds. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Flatirons soil is slow. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is slow, and water erosion and soil blowing are slight hazards. The shrink-swell potential is moderate. Rock fragments make up 35 to 80 percent of the volume.

This soil is used mainly for grazing and as habitat for wildlife and recreation areas. In a few areas it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, needleandthread, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of desirable plants and to prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. This soil is difficult to revegetate; therefore, proper grazing use is needed to prevent depletion. Mechanical treatment is not practical because the surface is stony. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain on this soil because of the large stones. Applications of manure and commercial fertilizers that contain nitrogen and phosphorus are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Pebbles and cobbles in disturbed areas should be removed from the surface for best results in landscaping, particularly for lawns. Supplemental irrigation is needed at planting time and during dry periods.

The areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate heavy flows to prevent flooding downslope in areas that normally would not be subject to flooding.

This Flatirons soil is limited for homesite development by the large stones, the shrink-swell potential, and the slow permeability. Excavating this soil for buildings and roads is difficult because of the large stones, and large equipment may be needed. The effects of shrinking and swelling can be minimized by proper engineering design and by backfilling with material that has a low shrink-swell potential and installing surface and subsurface drains near foundations. Properly installed tile drains below the foundation and minimal surface watering near the foundation help prevent seepage into basements and minimize the effects of shrinking and swelling. Special sewage systems must be installed because of the slow permeability. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

46-Flatirons very stony sandy loam, 0 to 5 percent slopes. This is a deep, well drained soil on undulating, dissected fan piedmonts. It formed in noncalcareous, cobbly, stony, gravelly, and loamy material of the Rocky Flats Alluvium. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 6,000 to 6,600 feet.

Typically, the surface layer is neutral and slightly acid, very dark grayish brown very stony sandy loam about 13 inches thick. The subsoil in the upper 8 inches is medium acid, reddish brown very gravelly clay; in the next 26 inches it is slightly acid and neutral, strong brown very gravelly sandy clay; and below that to a depth of 60 inches it is neutral, strong brown very gravelly sandy clay loam.

Included in mapping are small areas of calcareous soils near the edge of terraces, Veldkamp soils in positions similar to those of the Flatirons soil, and soils that have a very cobbly surface layer and are near the eastern limit of the map unit. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Flatirons soil is slow. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is slow, and water erosion and soil blowing are slight hazards. The shrink-swell potential is moderate. Rock fragments make up 35 to 80 percent of the volume.

In most places this soil is used for grazing and as wildlife habitat and recreation areas. In a few places it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, needleandthread, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of desirable plants and prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. This soil is difficult to revegetate; therefore, proper grazing use is needed to prevent depletion. Mechanical treatment is not practical because the surface is stony. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain on this soil because of the large stones. Applications of manure and commercial fertilizers that contain nitrogen and phosphorus are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Supplemental irrigation is needed at planting time and during dry periods.

The areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading Must accommodate heavy flows to prevent flooding downslope in areas that normally would not be subject to flooding.

This Flatirons soil is limited for use as homesites by the large stones, the shrink-swell potential, and the slow permeability. Excavating this soil for buildings and roads is difficult because of the large stones, and large equipment may be needed. The effects of shrinking and swelling can be minimized by proper engineering design and by backfilling with material that has a low shrink-swell potential and installing surface and subsurface drains near foundations. Properly installed tile drains below the foundation and minimal surface watering near the foundation help prevent seepage into basements and minimize the effects of shrinking and swelling. Special sewage systems must be installed because of the slow permeability. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

47-Flatirons very stony sandy loam, 5 to 9 percent slopes. This is a deep, well drained soil on piedmonts and hill slopes. It formed in noncalcareous, cobbly, stony, gravelly, and loamy material of the Rocky Flats Alluvium. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 6,000 to 6,800 feet.

Typically, the surface layer is neutral and slightly acid, dark grayish brown very stony sandy loam about 13 inches thick. The subsoil in the upper 8 inches is medium acid, reddish brown very gravelly clay; in the next 26 inches it is slightly acid and neutral, strong brown very gravelly sandy clay; and below that to a depth of 60 inches it is neutral, strong brown very gravelly sandy clay loam.

Included in mapping are small areas of Nederland soils on terrace escarpments, soils that have soft, reddish shale at a depth of 20 to 40 inches and are on convex shoulders and back slopes, and Veldkamp soils in positions similar to those of the Flatirons soil. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Flatirons soil is slow. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is medium, and water erosion is a moderate hazard. Soil blowing is a slight hazard. The shrink-swell potential is moderate. Rock fragments make up 35 to 80 percent of the volume.

This soil is used mainly for grazing and as wildlife habitat and recreation areas. In a few places it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, needleandthread, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of desirable plants and to prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. This soil is difficult to revegetate; therefore, proper grazing use is needed to prevent depletion. Mechanical treatment is not practical because the surface is stony. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain on this soil because of the large stones. Applications of manure and commercial fertilizers that contain nitrogen and phosphorus are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Planting on the contour helps to conserve moisture and reduce erosion. Supplemental irrigation is needed at the time of planting and during dry periods.

The small areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate increased flows to prevent flooding downslope in areas that normally would not be subject to flooding.

The Flatirons soil is limited for homesite development by the large stones, the shrink-swell potential, and the slow permeability. Excavating this soil for buildings and roads is difficult because of the large stones, and large equipment may be needed. The effects of shrinking and swelling can be minimized by proper engineering design and by backfilling with material that has a low shrink-swell potential and installing surface and subsurface drains near foundations. Properly installed tile drains below the foundation and minimal surface watering near the foundation help prevent seepage into basements and minimize the effects of shrinking and swelling. Special sewage systems must be installed because of the slow permeability. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

48-Flatirons very stony sandy loam, 9 to 15 percent slopes. This is a deep, well drained soil on hill slopes and ridges. It formed in noncalcareous, cobbly, stony, gravelly, and loamy material of the Rocky Flats Alluvium. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 6,000 to 6,800 feet.

Typically, the surface layer is neutral and slightly acid, very dark grayish brown very stony sandy loam about 13 inches thick. The subsoil in the upper 8 inches is medium acid, reddish brown very gravelly clay; in the next 26 inches it is slightly acid and neutral, strong brown very gravelly sandy clay; and below that to a depth of 60 inches it is neutral, strong brown very gravelly sandy clay loam.

Included in mapping are small areas of Nederland soils on terrace escarpments, soils that have soft, reddish shale at a depth of 20 to 40 inches and are on convex shoulders and back slopes, and Veldkamp soils in positions similar to those of the Flatirons soil. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Flatirons soil is slow. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is rapid, and water erosion is a severe hazard. Soil blowing is a slight hazard. The shrink-swell potential is moderate. Rock fragments make up 35 to 80 percent of the volume.

In most places this soil is used for grazing and as wildlife habitat and recreation areas. In a few places it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, needleandthread, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of desirable plants and to prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. This soil is difficult to revegetate; therefore, proper grazing use is needed to prevent depletion. Mechanical treatment is not practical because the surface is stony. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain on this soil because of the large stones and the slope. A mulch of plant residue helps to reduce runoff, improve tilth, and conserve moisture. Applications of manure and commercial fertilizers that contain nitrogen and phosphorus are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Planting on the contour helps to conserve moisture and reduce erosion. Supplemental irrigation is needed at planting time and during dry periods.

The small areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate increased flows to prevent flooding downslope in areas that normally would not be subject to flooding.

The main limitations to the use of this Flatirons soil for homesite development are the large stones, the shrink-swell potential, the slope, and the slow permeability. Excavating this soil for buildings and roads is difficult because of the large stones, and large equipment may be needed. The effects of shrinking and swelling can be minimized by proper engineering design and by backfilling with material that has a low shrink-swell potential and controlling surface and subsurface drainage near foundations. Properly installed tile drains below the foundation and minimal surface watering near the foundation help prevent seepage into basements and minimize the effects of shrinking and swelling. Special sewage systems must be installed because of the slow permeability. Cuts and fills should be seeded or mulched. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

49-Flatirons very stony sandy loam, 15 to 30 percent slopes. This is a deep, well drained soil on hill slopes and ridges. It formed in noncalcareous, cobbly, stony, gravelly, and loamy material of the Rocky Flats Alluvium. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 6,000 to 6,800 feet.

Typically, the surface layer is neutral and slightly acid, very dark grayish brown very stony sandy loam about 13 inches thick. The subsoil in the upper 8 inches is medium acid, reddish brown very gravelly clay; in the next 26 inches, it is slightly acid and neutral, strong brown very gravelly sandy clay; and below that to a depth of 60 inches it is neutral, strong brown very gravelly sandy clay loam.

Included in mapping are small areas of Nederland soils on terrace escarpments, soils that have soft, reddish shale at a depth of 20 to 40 inches and are on convex shoulders and back slopes, and Veldkamp soils in positions similar to those of the Flatirons soil. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Flatirons soil is slow. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is rapid, and water erosion is a severe hazard. Soil blowing is a slight hazard. The shrink-swell potential is moderate. Rock fragments make up 35 to 80 percent of the volume.

This soil is used mainly for grazing and as habitat for wildlife and recreation areas. In a few places it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, needleandthread, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of desirable plants and to prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. Proper grazing use is needed to prevent depletion because this soil is difficult to revegetate. Mechanical treatment is not practical because the surface is stony. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain on this soil because of the large stones and the slope. A mulch of plant residue helps reduce runoff, improve tilth, and conserve moisture. Applications of manure and commercial fertilizers that contain nitrogen and phosphorus are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Planting on the contour helps to conserve moisture and reduce erosion. Supplemental irrigation is needed at planting time and during dry periods.

The areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate heavy flows to prevent flooding downslope in areas that normally would not be subject to flooding.

The main limitations to use of this Flatirons soil for homesite development are large stones, the shrink-swell potential, the slope, and the slow permeability. Excavating this soil for buildings and roads is difficult because of the large stones, and large equipment may be needed. The effects of shrinking and swelling can be minimized by proper engineering design and by backfilling with material that has a low shrink-swell potential and installing surface and subsurface drains near foundations. Properly installed tile drains below the foundation and minimal surface watering near the foundation help prevent seepage into basements and minimize the effects of shrinking and swelling. Special sewage systems must be installed because of the slope and the slow permeability. Cuts and fills should be seeded or mulched. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

G.2 Nederland Series

The Nederland series consists of deep, well drained soils on piedmont fan terraces, alluvial terraces, stable summits, and terrace escarpments. Nederland soils formed in cobbly, gravelly, and loamy alluvium derived from mixed sources. The slope is 0 to 50 percent average annual precipitation is 15 to 17 inches. The average annual temperature is 47°F. The average frost-free season ranges from 126 to 142 days. Elevation ranges from 5,600 to 6,500 feet.

These soils are loamy-skeletal, mixed, mesic Acidic Argiustolls.

Typical pedon of Nederland very cobbly sandy loam, in an area of Veldkamp-Nederland very cobbly sandy loams, 0 to 3 percent slopes, 1,050 feet east and 200 feet north of the southwest corner of the northwest quarter of sec. 33, T. 2 S., R. 70 W.

Al-0 to 7 inches; dark brown (1 OYR 3/3) very cobbly sandy loam, very dark brown (10YR 2/2) moist; weak fine granular structure; soft, very friable, slightly sticky; few stones, 40 percent cobbles, 20 percent gravel; mildly alkaline; clear smooth boundary.

A3-7 to 10 inches; brown to dark brown (7.5YR 4/2) very cobbly sandy loam, dark brown (7.5YR 3/2) moist; weak medium subangular blocky structure; slightly hard, very friable, slightly sticky; few stones, 40 percent cobbles, 20 percent gravel; mild alkaline; clear smooth boundary.

B21t-10 to 21 inches; dark brown (7.5YR 3/4) very cobbly sandy clay loam, dark brown (7/5YR 3/4) moist; moderate medium subangular blocky structure parting to moderate medium granular;

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hard, very friable, sticky; 40 percent cobbles, 20 percent gravel; common moderately thick clay films on faces of peds; neutral; gradual wavy boundary.

B22t-21 to 38 inches; strong brown (7.5YR 4/6) very cobbly sandy clay loam, strong brown (7.5YR 4/6) moist; moderate medium subangular blocky structure parting to moderate medium granular; hard, very friable, sticky; 10 percent stones, 30 percent cobbles, 20 percent gravel; common moderately thick clay films on faces of peds; neutral; gradual wavy boundary.

B3-38 to 62 inches; strong brown (7.5YR 4/6) very cobbly sandy clay loam, strong brown (7.5YR 4/6) moist; weak coarse subangular blocky structure; hard, very friable, sticky; 5 percent stones, 25 percent cobbles, 30 percent gravel; few this clay films on faces of peds; neutral; gradual wavy boundary.

C-62 to 70 inches; strong brown (7.5YR 4/6) very stony sandy loam, strong brown (7.5YR 4/6) moist; single grained; loose, slightly sticky; 20 percent stones, 20 percent cobbles, 20 percent gravel; neutral.

The mollic epipedon is 7 to 19 inches thick. The solum than is more than 20 inches thick. The content of rock fragments ranges from 35 to 75 percent throughout. The fragments are dominantly 10 inches or less in diameter. In most places the soils are noncalcareous. Reaction is neutral to mildly alkaline.

The A horizon has hue of 10YR or 7.5YR, value of 3 to 5 dry and 2 or 3 moist, and chroma of 2 or 3.

The B horizon has hue of 10YR or 7.5YR, value of 3 to 5 and 3 or 4 moist, and chroma of 4 to 6. The clay content is 20 to 35 percent.

The C horizon has hue of 10YR or 7.5YR. It is very cobbly sandy loam or very stony sandy loam. In some places it is at a depth of less than 60 inches.

The absence of hues redder than 7.5YR and a solum more than 60 inches thick place the Nederland soils out of the range established for the series. Thus, Nederland soils in this survey area are a taxadjunct to the series.

100-Nederland very cobbly sandy loam, 15 to 50 percent slopes. This is a deep, well drained soil on shoulders and back slopes of terrace escarpments. This soil formed in cobbly, gravelly, and loamy alluvium derived from mixed sources. The average annual precipitation is15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 5,600 to 6,500 feet.

Typically, the surface layer is mildly alkaline, dark brown and brown very cobbly sandy loam about 10 inches thick. The subsoil is neutral, dark brown and strong brown very cobbly sandy clay loam about 50 inches thick.

Included in mapping are small areas of Willowman soils on terrace escarpments, Flatirons and Veldkamp soils on terraces, Primen and Leyden soils on hill slopes at the lower edge of the mapped areas, and wet areas below springs. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Nederland soil is moderate. The available water capacity is moderate. The effective rooting depth is 60 inches or more. Runoff is rapid, and water erosion is a severe hazard. Soil blowing is a slight hazard. The shrink-swell potential is low. Rock fragments make up 35 to 75 percent of the volume.

In most areas this soil is used for grazing, as pasture, and as habitat for wildlife. In a few areas it is used for community development.

The native vegetation is mainly big bluestem, little bluestem, blue grama, mountain muhly, and, on north-facing slopes, mountainmahogany. The average annual reduction of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity desirable plants and to prevent erosion. Proper grazing use is needed to prevent depletion because this soil is difficult to revegetate. Periodic deferment of grazing during the growing season helps maintain or improve the range condition.

The steepness of the slopes limits access by livestock and promotes overgrazing of the less sloping areas. The use of machinery is not practical because the surface is stony and the slopes are steep. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain because of the slope and large stones. A mulch of plant residue helps reduce runoff, improve tilth, and conserve moisture. Applications of manure and of nitrogen and phosphate fertilizers are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Planting on the contour helps conserve moisture and reduce erosion. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Supplemental irrigation is needed at the time of planting and during dry periods.

The small areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate heavy flows to prevent flooding downslope in areas that normally would not be subject to flooding.

The main limitations to use of the soil for homesite development are the slope and large stones. The hazard of erosion increases if the soil is left exposed during site development. Structures to divert runoff from buildings and roads are needed. The steepness of the slope is a limitation for septic tank absorption fields. Absorption lines should be installed on the contour. Effluent from an absorption field can surface downslope and create a health hazard. Cuts and fills should be seeded or mulched. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

This soil is in capability subclass Vile, in the Cobbly Foothill range site, and in plant adaptability group F-5.

101-Nederland Variant very cobbly sandy loam, 30 to 50 percent slopes. This is a deep, well drained soil on hill slopes and ridges of Green Mountain. This soil formed in cobbly, gravelly, and loamy alluvium derived from mixed sources. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47□ F, and the average frost-free season is 126 to 142 days. Elevation is 6,200 to 6,900 feet.

Typically, the surface layer is medium acid, brown to dark brown very cobbly sandy loam about 3 inches thick. The subsoil in the upper 5 inches is medium acid, brown to dark brown very cobbly sandy loam. In the lower 9 inches it is neutral, brown to dark brown very cobbly sandy loam. The substratum to a depth of 60 inches is neutral, yellowish brown very cobbly loamy sand.

Included in mapping are small areas of Veldkamp soils on stable summits, Nederland soils on terraces, Rooney soils on hill slopes at the lower edge of some mapped areas, and Leyden and Primen soils on hill slopes. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

Permeability of this Nederland Variant soil is moderately rapid to rapid. The available water capacity is low. The effective rooting depth is 60 inches or more. Runoff is rapid, and water erosion is a severe hazard. Soil blowing is a slight hazard. The shrink-swell potential is low. Rock fragments make up 35 to 65 percent of the volume.

This soil is used mainly for grazing (fig. 4) and as Pasture, as habitat for wildlife, and as recreation areas. In a few places this soil is used for community development.

The native vegetation is mainly big bluestem, little bluestem, blue grama, mountain muhly, and, on north-facing slopes, mountainmahogany. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of the desirable plants an prevent erosion. Proper grazing use is needed to prevent depletion because this soil is difficult to revegetate. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. The steepness of the slopes limits access by livestock and promotes overgrazing of the less sloping areas. The use of machinery is not practical because of the stony surface and steep slopes. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

Grasses, shrubs, trees, and garden plants are difficult to establish and maintain because of the slope and large stones. A mulch of plant residue helps reduce runoff, improve tilth, and conserve moisture. Applications of manure and of nitrogen and phosphate fertilizers are needed to maintain fertility. Selecting adapted plants is essential in establishing plantings. Planting on the contour helps conserve moisture and reduce erosion. Pebbles and cobbles on the surface should be removed for best results in landscaping, particularly for lawns. Supplemental irrigation is needed at the time of planting and during dry periods.

The small areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must heavy flows to prevent flooding areas that normally would not be subject to flooding.

The main limitations to use of the soil for homesite development are the slope and large stones. The hazard of erosion increases if the soil is left exposed during site development. Structures to divert runoff are needed to protect buildings and roads. The steep slopes are a limitation for septic tank absorption fields. Absorption lines should be installed on the contour. Effluent from an absorption field can surface downslope and create a health hazard. Cuts and fills should be seeded or mulched. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

The soil is in capability subclass VIIe, in the Cobbly Foothill range site, and in plant adaptability group F-5.

G.3 Nederland Variant

The Nederland Variant consists of deep, well drained soils on hill slopes and ridges of Green Mountain. Nederland Variant soils formed in cobbly, gravelly, and loamy alluvium derived from mixed sources. The slope is 30 to 50 percent. The average annual precipitation is 15 to 17 inches. The average annual temperature is 47°F. The average frost-free season ranges from 126 to 142 days. Elevation ranges from 6,200 to 6,900 feet.

These soils are loamy-skeletal, mixed, mesic Aridic Argiustolls.

Typical pedon of Nederland Variant very cobbly sandy loam, 30 to 50 percent slopes, 950 feet west and 360 feet south of the northeast corner of the northwest quarter of sec. 19, T. 4 S., R. 69 W.

A1-0 to 3 inches; brown to dark brown (1 OYR 4/3) very cobbly sandy loam, very dark grayish brown (10YR 3/2) moist; weak fine granular structure; soft, very friable, nonsticky; 20 percent cobbles, 30 percent gravel; medium acid; clear smooth boundary.

B21t-3 to 8 inches; brown to dark brown (10YR 4/3) very cobbly sandy loam, very dark grayish brown (10YR 3/2) moist; weak fine granular structure; soft, very friable, nonsticky; 20 percent cobbles, 30 percent gravel; medium acid; clear smooth boundary.

B22t-8 to 17 inches; brown to dark brown (10YR 4/3) very cobbly sandy loam, dark brown (10YR 3/3) moist; weak fine granular structure; soft, very friable, nonsticky; 25 percent cobbles, 25 percent gravel; neutral; gradual wavy boundary.

C-17 to 60 inches; yellowish brown (10YR 5/6) very cobbly loamy sand, dark yellowish brown (10YR 4/4) moist; single grained; loose, nonsticky; 30 percent cobbles, 30 percent gravel; neutral.

The solum is 15 to 40 inches thick. The content of rock fragments ranges from 35 to 65 percent. The fragments are dominantly gravel and cobbles. The soil is noncalcareous to a depth of 40 inches or more. Reaction is neutral to medium acid.

The A horizon has hue of 10YR or 7.5YR, value of 4 or 5 dry and 2 or 3 moist, and chroma of 2 or 3.

The B horizon has hue of 10YR or 7.5YR, value of 4 to 6 dry and 3 to 5 moist, and chroma of 2 or 3. The clay content is 10 to 18 percent.

The C horizon has hue of 10YR or 7.5YR. It is stratified very cobbly loamy sand.

G.4 Veldkamp-Nederland

169-Veidkamp-Nederiand very cobbly sandy loams, 0 to 3 percent slopes. These soils are on Piedmont fan terraces, alluvial terraces, and stable summits. The average annual precipitation is 15 to 17 inches, the average annual air temperature is 47°F, and the average frost-free season is 126 to 142 days. Elevation is 5,600 to 6,500 feet.

Veldkamp soil makes up 65 percent of this map unit, and Nederland soil makes up 20 percent. Veldkamp and Nederland soils are in similar positions on the landscape. The areas of these soils are so intricately intermingled that it was not practical to map them separately.

Included in mapping are small areas of Valmont soils on high terraces, Willowman soils on terrace escarpments, and Standley soils on terraces and hill slopes. Standley soils have a lower percentage of rock fragments than Veldkamp and Nederland soils. Also included are small areas of Urban land. The included soils and Urban land make up about 15 percent of the total acreage.

The Veldkamp soil is deep and well drained. It formed in noncalcareous, stratified, cobbly, gravelly, and clayey alluvial material.

Typically, the surface layer is neutral, dark grayish brown very cobbly sandy loam about 3 inches thick. The subsoil in the upper 9 inches is neutral, dark grayish brown and brown to dark brown very cobbly clay loam and very cobbly clay. In the lower 9 inches it is neutral, dark yellowish brown very cobbly clay loam. The substratum to a depth of 60 inches is neutral, dark yellowish brown, stratified very cobbly sandy loam.

Permeability of the Veldkamp soil is moderately slow. The available water capacity is moderate. The effective rooting depth is 60 inches or more. Runoff is slow. Water erosion and soil blowing are slight hazards. The shrink-swell potential is moderate. Rock fragments make up 35 to 60 percent of the-volume.

The Nederland soil is deep and well drained. It formed in cobbly, gravelly, and loamy alluvium derived from mixed sources.

Typically, the surface layer is mildly alkaline, dark brown to brown very cobbly sandy loam about 10 inches thick. The subsoil is neutral, dark brown and strong brown very cobbly sandy clay loam about 52 inches thick. The substratum below a depth of 62 inches is neutral, strong brown very stony sandy loam.

Permeability of the Nederland soil is moderate. The available water capacity is moderate. The effective rooting depth is 60 inches or more. Runoff is slow. Water erosion and soil blowing are slight hazards. The shrink-swell potential is low. Rock fragments make up 35 to 75 percent of the volume.

In most places the soils are used for grazing and as habitat for wildlife. In a few places they are used for community development.

The native vegetation is mainly big bluestem, little bluestem, blue grama, and mountain muhly. The average annual production of air-dry vegetation ranges from 1,000 to 2,300 pounds per acre. Proper grazing use and a planned grazing system are needed to maintain the quality and quantity of the desirable plants and to prevent erosion. Periodic deferment of grazing during the growing season helps maintain or improve the range condition. Large stones on the surface make seeding difficult and mechanical treatment impractical. Small pastures commonly are severely overgrazed and eroded. Livestock in small pastures should be kept in pens. The rest of the pasture can be used as exercise areas and for very limited grazing.

The establishment and maintenance of grasses, shrubs, trees and garden plants are limited by the large stones, which make tillage difficult. Pebbles and cobbles should be removed from the surface for best results in landscaping, particularly for lawns. Mulching, fertilizing, and irrigation are needed to establish grasses and other plants. Selecting adapted plants is essential in establishing plantings.

The areas of Urban land are covered by streets, parking lots, sidewalks, buildings, and other impervious manmade structures. Because runoff is rapid, storm drains, natural drainageways, and land grading must accommodate increased flows to prevent flooding downslope in areas that normally would not be subject to flooding.

The main limitation to use of the soils for homesite development is the large stones. Excavation of buiding sites and roads is difficult because of the large stones and may require the use of large equipment. Erosion and sedimentation can be controlled by maintaining an adequate plant cover.

These soils are in capability subclass VIIs, in the Cobbly Foothill range site, and in plant adaptability group F-5.

G.5 Veldkamp Series

The Veldkamp series consists of deep, well drained soils on alluvial terraces, stable summits, and piedmont fan terraces. Veldkamp soils formed in noncalcareous, stratified, cobbly, gravelly, and clayey alluvial material. The slope is 0 to 3 percent. The average annual precipitation ranges from 13 to 17 inches, and the average annual temperature is 47°F. The frost-free season ranges from 126 to 142 days. Elevation ranges from 5,200 to 6,500 feet.

These soils are clayey-skeletal, mixed, mesic Aridic Argiustolls.

Typical pedon of Veldkamp very cobbly sandy loam, in an area of Veldkamp-Nederland very cobbly sandy loams, 0 to 3 percent slopes, 105 feet north and 100 feet west of the southeast corner of the southwest quarter of sec. 2, T. 3 S., R. 70 W.

Al -0 to 3 inches; dark grayish brown (10YR 4/2) very cobbly sandy loam, very dark grayish brown (10YR 3/2) moist; weak fine granular structure; slightly hard, friable, slightly sticky; 20 percent cobbles, 20 percent gravel; neutral; clear smooth boundary.

B21 t-3 to 6 inches; dark grayish brown (10YR 4/2) very cobbly clay loam, very dark grayish brown (10YR 3/2) moist; moderate medium subangular blocky structure parting to moderate medium granular; hard, firm, sticky; 20 percent cobbles, 20 percent gravel; few thin clay films on faces of peds and as coatings on rock fragments; neutral; clear smooth boundary. 822t-6 to 12 inches; brown to dark brown (10YR 4/3) very cobbly clay, dark brown (10YR 3/3) moist; moderate medium subangular blocky structure parting to moderate fine subangular blocky;

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hard, firm, very sticky; 20 percent cobbles, 20 percent gravel; common moderately thick clay films on faces of peds and as coatings on rock fragments; neutral; clear smooth boundary.

B23t -12 to 21 inches; dark yellowish brown (10YR 4/4) very cobbly clay loam, dark yellowish brown (10YR 3/4) moist; moderate medium subangular blocky structure parting to moderate fine subangular blocky; hard, firm, sticky; 20 percent cobbles, 20 percent gravel; few thin clay films on faces of peds and as coatings on rock fragments; neutral; clear wavy boundary.

IIC-21 to 60 inches; dark yellowish brown (10YR 4/4) stratified very cobbly sandy loam, dark yellowish brown (10YR 3/4) moist; massive; slightly hard, friable, slightly sticky; 20 percent cobbles, 20 percent gravel; neutral.

The mollic epipedon is 7 to 20 inches thick. The solum is 15 to 30 inches thick. The content of rock fragments ranges from 35 to 60 percent. Reaction is neutral or mildly alkaline.

The A horizon has hue of 7.5YR to 2.5Y, value of 3 to 5 dry and 2 or 3 moist, and chroma of 2 or 3.

The B2t horizon has hue of 7.5YR to 2.5Y, value of 3 to 6 dry and 2 to 5 moist, and chroma of 3 to 5. Soil that has value of 2 or 3 (moist) is at a depth of less than 20 inches. The B2t horizon commonly is very cobbly. The clay content is 35 to 50 percent.

The C horizon has hue of 7.5YR to 2.5Y. It is stratified and commonly is very cobbly. The clay content is 8 to 25 percent.

Appendix H

Geotechnical Results for Candidate Off-Site Borrow Soil

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Summary of Tests Performed

Laboratory Sample Number	Initial Soil Properties[1] (θ, ρ_d, ϕ)	Saturated Hydraulic Conductivity[2]		Moisture Characteristics[3]					Unsaturated Hydraulic Conductivity	Particle Size[4]			Effective Porosity	Particle Density	Air Permeability	1/3, 15 Bar Points and Water Holding Capacity	Atterberg Limits	Proctor Compaction
		CH	FH	HC	PP	TH	WP	RH		DS	WS	H						
RF-Proctor											X	X					X	X
RF-1	X	X		X	X		X	X	X									
RF-2	X	X		X	X		X	X	X									

[1] θ = Initial moisture content, ρ_d = Dry bulk density, ϕ = Calculated porosity
[2] CH = Constant head, FH = falling head
[3] HC = Hanging column, PP = Pressure plate, TH = Thermocouple psychrometer, WP = Water activity meter, RH = Relative humidity box
[4] DS = Dry sieve, WS = Wet sieve, H = Hydrometer

Summary of Initial Moisture Content, Dry Bulk Density Wet Bulk Density and Calculated Porosity

Sample Number	Initial Moisture Content Gravimetric (%, g/g)	Initial Moisture Content Volumetric (%, cm^3/cm^3)	Dry Bulk Density (g/cm^3)	Wet Bulk Density (g/cm^3)	Calculated Porosity (%)
RF-1	8.5	13.0	1.53	1.66	42.1
RF-2	8.1	13.1	1.63	1.76	38.6

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Summary of Saturated Hydraulic Conductivity Tests

Sample Number	K_{sat} (cm/sec)	Method of Analysis: Constant Head	Method of Analysis: Falling Head
RF-1	4.5E-03	X	
RF-2	5.1E-04	X	

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Summary of Calculated Unsaturated Hydraulic Properties

Sample Number	α (cm^{-1})			N (dimensionless)				
	Calculated Value	95% Confidence Limits Lower	95% Confidence Limits Upper	Calculated Value	95% Confidence Limits Lower	95% Confidence Limits Upper	θ_r	θ_s
RF-1	0.1531	0.0000	0.3727	1.1829	1.0481	1.3176	0.0023	0.4309
RF-2	0.0595	0.0006	0.1184	1.1721	1.1367	1.2074	0.0000	0.3836

Summary of Moisture Characteristics of the Initial Drainage Curve

Sample Number	Pressure Head (-cm water)	Moisture Content (%, cm^3/cm^3)
RF-1	0	42.1
	10	40.8
	27	31.7
	37	29.3
	77	25.8
	255	21.3
	337	20.6
	1020	18.6
	9484	12.7
	17133	11.6
	851293	3.7
RF-2	0	38.6
	17	34.2
	146	25.4
	337	22.9
	510	22.2
	9484	13.5
	17133	12.3
	851293	3.9

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Summary of Particle Size Characteristics

Sample Number	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	C_u	C_c	Method	ASTM Classification	USDA Classification
RF-Proctor	0.0053	0.70	1.2	226	8.3	WS/H	Clayey sand with gravel	Sandy Loam

d_{50} = Median particle diameter

Est = Reported values for d_{10}, C_u, C_c, and soil classification are estimates, since extrapolation was required to obtain the d_{1n} diameter

$$C_u = \frac{d_{60}}{d_{10}}$$

$$C_c = \frac{(d_{30})^2}{(d_{10})(d_{60})}$$

DS = Dry sieve

H = Hydrometer

WS = Wet sieve

Summary of Atterberg Tests

Sample Number	Liquid Limit	Plastic Limit	Plasticity Index	Classification
RF-Proctor	33.1	21.5	11.6	CL

--- = Soil requires visual-manual classification due to non-plasticity

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Summary of Proctor Compaction Tests

Sample Number	Optimum Moisture Content (% g/g)	Maximum Dry Bulk Density (g/cm^3)
RF-Proctor	11.5	1.92

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Appendix I

Runoff Calculations

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Modeling Methodology to Determine Runoff at the Present Landfill Closure Cover Rocky Flats Environmental Technology Site

Prepared for Kaiser-Hill, LLC
Golden, Colorado

April 15, 2002

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Appendix I.
Modeling Methodology to Determine Runoff at the Present Landfill Closure Cover Rocky Flats Environmental Technology Site

I.1 Introduction

Runoff from the Present Landfill at the Rocky Flats Environmental Technology Site (RFETS) was estimated using two methods: (1) the Rational Method and (2) the Colorado Urban Hydrograph Procedure (CUHP). The following is a description of the estimation methods and a discussion of the results. The Rational Method and its inputs will be discussed first followed by the CUHP.

I.2 Rational Method

The Rational Method, first employed in 1889, is the most widely used and accepted method for modeling small watersheds. The Rational Method is based on the Rational Formula:

$$Q = CIA \tag{1}$$

where:

Q = the maximum rate of runoff (cubic feet second [cfs])

C = a runoff coefficient that is the ratio between the runoff volume from an area and the average rate of rainfall depth over a given duration for that area

I = average intensity of rainfall (inches per hour) for a duration equal to the time of concentration, tc

A = area (acres).

The Rational Method can be performed by hand, however the Denver Urban Drainage and Flood Control District (DUDFCD) has developed a spreadsheet to automate the calculations and provide regional constants. This spreadsheet was used for modeling runoff and infiltration for the landfill cover.

The Rational Method spreadsheet developed by the DUDFCD requires the following inputs:

- Area (acres)
- Percent imperviousness (%)
- NRCS soil type (A, B, C, or D)
- Design storm return period, Tr (years)
- Runoff coefficients, C1, C2, and C3
- One-hour precipitation, P1 (inches)
- Slope (ft/ft)
- Length of the flow path (feet)

As an option the user may input Runoff Coefficient, C, and Runoff Coefficient, C-5, thus overriding the recommended values.

The spreadsheet then calculates:

- Computed time of concentration, Tc (minutes)
- Regional time of concentration, Tc (minutes)
- Rainfall intensity, I, using the computed time of concentration (inches per hour [in/hr])
- Peak flowrate, Qp, using the computed time of concentration, (cfs)
- Rainfall intensity, I, using the regional time of concentration (in/hr)
- Peak flowrate, Qp, using the regional time of concentration, (cfs)

The computed time of concentration and the regional time of concentration are computed so the user may compare the empirical time of concentration limit used for the Denver region with the calculated value. The smaller of the two time of concentration values should be used to compute rainfall duration.

The area modeled is shown in Figure I-1. This area was divided into six sub-basins based on slope and direction of overland flow. The location of each sub-basin is also presented in Figure I-1. The area, average length of flow path, and slope were determined for each of the six sub-basins. These values are presented in Table I-1.

Table I-1. Sub-Basin Areas, Flow Path Lengths, and Slopes

Sub-Basin	Area (acres)	Area (sq. miles)	Average Flow Path (feet)	Average Flow Path (miles)	Slope (ft/ft)
1	8.51	0.0133	350	0.07	0.05
2	7.05	0.0110	350	0.07	0.05
3	12.40	0.0194	600	0.11	0.04
4	8.24	0.0129	350	0.07	0.14
5	6.39	0.0100	300	0.06	0.04
6	1.07	0.0017	100	0.02	0.16

The NRCS soil type used for the cover is a required input parameter and, therefore, needed to be determined. The definitions of the four NRCS soil group classifications are given in *A Guide to Hydrolologic Analysis Using SCS Methods* (McCuen, 1982) as follows:

- A — deep sand, deep loesses, aggregated silts; minimum infiltration rate 0.30 - 0.45 in/hr
- B — shallow loesses, sandy loam; minimum infiltration rate 0.15 - 0.30 in/hr
- C — clay loams, shallow sandy loam, soils low in organic content, and soils unusually high in clay; minimum infiltration rate 0.05 - 0.15 in/hr
- D — soils that swell significantly when wet, heavy plastic clays, and certain saline soils; minimum infiltration rate 0.0 - 0.05 in/hr

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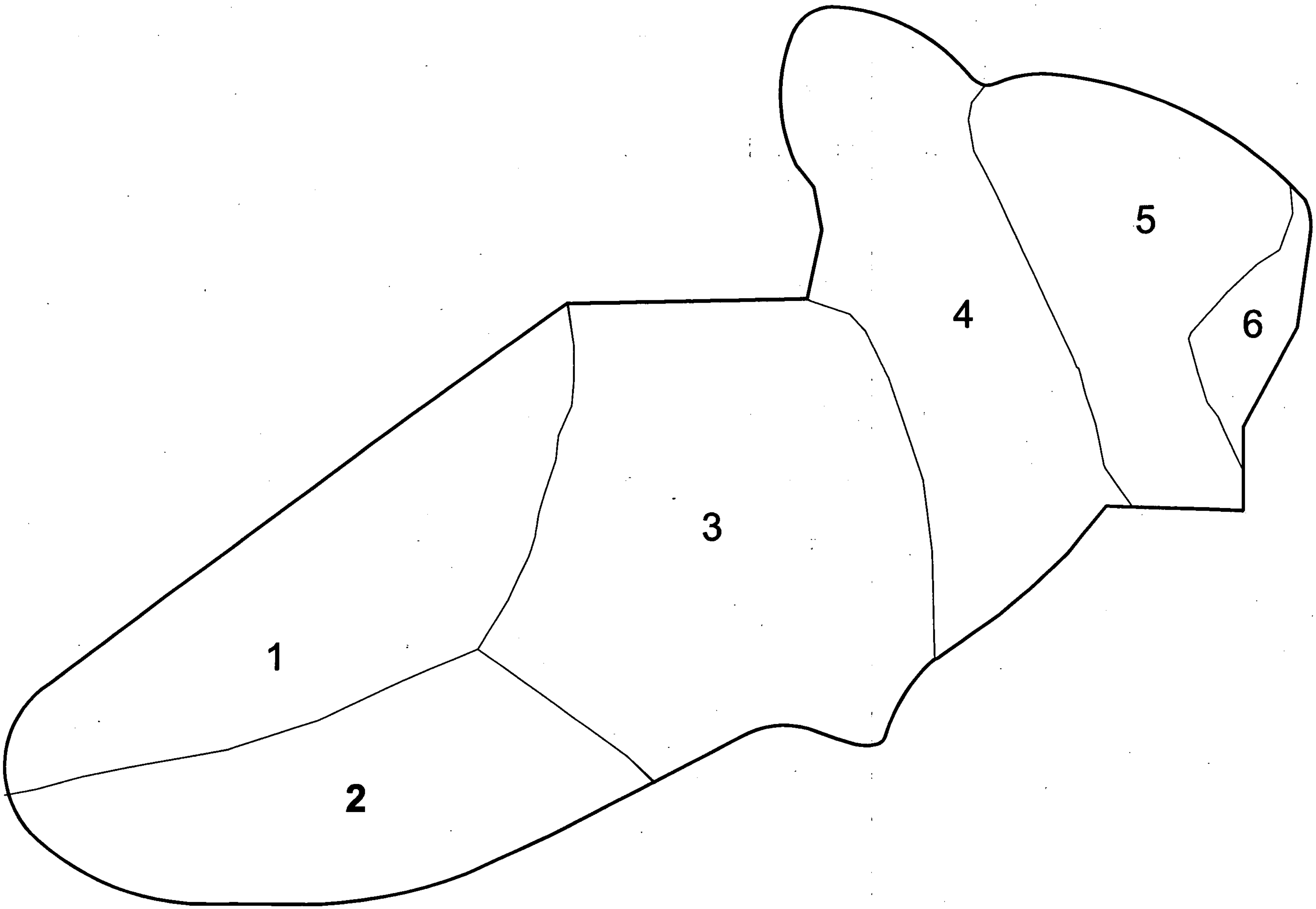

ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE
Present Landfill Sub-basins

Figure I-1

From these definitions it was determined that soil type A would be the most appropriate representation of this cover. The cover has no impervious sections so zero was entered for percent imperviousness.

Design storm return periods (Tr) of 100 years and 1,000 years were both modeled. The 1-hour precipitation for the 100-year storm was determined from the 100-year, 1-hour rainfall chart included in the Drainage Criteria Manual (V.1) developed by the DUDFCD (2001). From this chart, the 1-hour precipitation was determined to be 2.7 inches. To determine the 1--hour precipitation value for a 1,000-year storm, the 1-hour precipitation values from the 2-, 5-, 10-, 25-, 50-, and 100-year charts were graphed. The 1,000-year, 1-hour precipitation value was then extrapolated. The 1000-year, 1-hour precipitation value was determined to be 3.68 inches. The Denver default values for runoff coefficients C1, C2, and C3 were used and the default runoff coefficients C and C-5 were accepted.

The spreadsheet returns the computed Tc and the regional Tc. The smaller of these two values was used to calculate the rainfall intensity (I) and the peak flow rate (Qp). Rainfall intensity is calculated using the following empirical formula for the Denver region:

$$I = \frac{28.5 P_1}{(10 + T_c)^{0.786}} \qquad (2)$$

Tables I-2 and I-3 present the results of the 100- and 1,000-year storms.

Table I-2. Rainfall Intensity and Peak Flowrate for Each Sub-Basin for a 100-Year Storm

Sub-basin	Rainfall Intensity (in/hr)	Peak Flow Rate (cfs)
1	6.79	11.56
2	6.79	9.58
3	6.47	16.05
4	6.79	11.19
5	6.86	8.77
6	7.95	1.7
TOTAL		58.85

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Table I-3. Rainfall Intensity and Peak Flowrate for Each Sub-Basin for a 1,000-Year Storm

Sub-basin	Rainfall Intensity (in/hr)	Peak Flow Rate (cfs)
1	9.26	15.76
2	9.26	13.05
3	8.82	21.87
4	9.26	15.25
5	9.35	11.95
6	10.84	2.32
TOTAL		80.2

I.3 Colorado Urban Hydrograph Procedure (CUHP)

The CUHP is a method of hydrologic analysis based on the unit hydrograph principle. It has been developed and calibrated using rainfall-runoff data collected in Colorado (mostly in the Denver/Boulder metropolitan area).

The CUHP requires different inputs depending on the area to be modeled and the method of inputting rainfall data. For the Present Landfill cover, the areas were (for the most part) between the model basin categories of 5 to 90 acres and the 1-hour rainfall data option was selected. The following is a list of required inputs and the values that were entered for cover. Where the input value equals "varies" refer to the section for the specific cover for input information.

- Storm return period (years) = 100 and 1000 years
- 1-hour depth (inches) = 2.7 and 3.68 inches, respectively
- Unit duration of rainfall increments and unit hydrograph (minutes) = 5 minutes
- Catchment area (sq. miles) = varies
- Catchment length (miles) = varies
- Distance to centroid (miles) = varies

- Catchment imperviousness (percent) = 0.0%
- Weighted catchment slope (feet/foot) = varies
- Time of concentration (minutes) = varies
- Average maximum depression storage on pervious surfaces (inches) = 0.5 inches
- Average maximum depression storage on impervious surfaces (inches) = 0.0 inches
- Initial infiltration rate (in/hr) = 5.0 in/hr
- Horton's Exponential Decay Rate Coefficient (1/second) = 0.0007 s-1
- Final infiltration rate (in/hr) = 3.0 in/hr

Table I-1 lists the catchment area, length, and slope. Half of the length was entered for the distance to centroid. The time of concentration was taken from the Tc generated by the Rational Method spreadsheet and was approximately 10 minutes for all sub-basins.

The outputs from the CUHP for the 100-year and the 1,000-year storms are presented in Tables I-4 and I-5 respectively.

Table I-4. Rainfall Intensity and Peak Flowrate for Each Sub-Basin for a 100-Year Storm

Sub-basin	Rainfall Intensity (in/hr)	Peak Flow Rate (cfs)
1	6.8	0
2	6.8	0
3	6.5	1
4	6.8	0
5	6.8	0
6	7.1	0
TOTAL		1

Table I-5: Rainfall Intensity and Peak Flowrate for Each Sub-Basin for a 1,000-Year Storm

Sub-basin	Rainfall Intensity (in/hr)	Peak Flow Rate (cfs)
1	9.2	9
2	9.2	7
3	8.8	14
4	9.2	9
5	9.3	6
6	9.7	3
TOTAL		48

I.4 Conclusions

Runoff flow rates vary widely between the Rational Method spreadsheet and the CUHP model. One of the limitations with the Rational Method spreadsheet is that the input is limited to a NRCS soil type A, B, C, or D. Using the CUHP model the infiltration rate is input directly. Soil permeability is a very sensitive parameter, meaning that altering this one number can give widely varying results. The material used on the cover was selected with a high permeability. An infiltration rate of 3 to 5 in/hr was used for the CUHP. The drawback of the CUHP is that it is designed to be used with watersheds 90 acres or more, with an option for modeling areas between 5 and 90 acres using the Rational Method. The option for modeling smaller areas requires input for the time of concentration. Time of concentration is also a sensitive parameter. Each model has limitations, which is why both methods were used to model the cover and provide an estimated range of representative runoff values. The true value for the runoff, which will be strongly dependent on the final cover soil properties, likely lies within the range of values produced by the two models.

References

Urban Drainage and Flood Control District (DUDFCD). 2001. *Criteria Manual, Volume 1*. Wright Water Engineers, Inc., Project Consultant. Denver, Colorado. June 2001

McCuen, M. 1982. *A guide to hydrolologic analysis using SCS methods.* Prentice-Hall, Inc. Englewood Cliffs, NJ.